B-fields at NIF Workshop

- The workshop's charter is to capture the near term requirements for implementing researchers' plans for magnetic fields around targets, and to explore longer term, strategic needs.

- The workshop's charge is to document those near term and long-term requirements in the materials that come out of the presentations and discussions.

B-fields at NIF Workshop format

- Day 1 – talks focused on ICF applications
- Day 2 – talks focused around discovery science proposals

- All talks are to be kept short and informal, with an emphasis on the implementation of a B-field capability around a target rather than a deep dive into the interesting physics
- Significant amounts of time have been left unstructured for discussion following small sets of the talks

The viewgraphs submitted (hopefully on the requested template) will comprise the proceedings - notes and action items will be captured and relayed to the NIF director

B-fields at NIF Workshop day 1

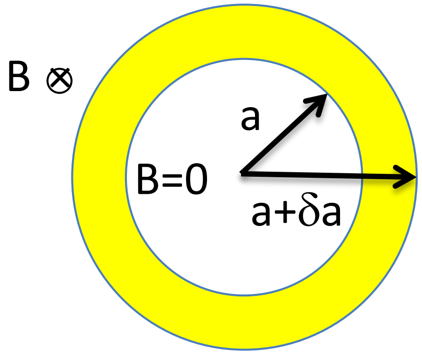
Monday, 10/12	
1300 - Introduction - Mark Herrmann/Doug Larson 1310 - Welcome - Ground rules - Kevin Fournier/John Moody	1620 - requirements re. laser-heated plasmas/discussion of NIF implementation
1315 - 01-ICF needs - Perkins et al. - Ignition Applications	1650 - 05-Direct Drive: PDD and Shock Ignition - Hohenberger (LLE) 1710 - 06-MIFEDS at OMEGA - G. Fiksel (LLE)
1345 - discussion - ICF requirements re. impact on ICF	1740 - discussion re. implementation issues
1415 - 02-ICF continued - hohlraum performance, LPI supression - D. Strozzi (LLNL), D. Montgomery (LANL)	1810 - 07-FACILITY AND MACHINE SAFETY ISSUES - VanWonterghem/Kalantar
1445 - ICF requirements/discussion re. NIF implementation	1840 - Day 1 report out - VanWonterghem/Fournier 1900 - adjourn
1515 - break	
1530 - 03-X-Ray Sources - Kemp (Colvin to present) (LLNL)	
1550 - 04-MagLIF - Adam Sefkow (SNL)	

B-fields at NIF Workshop day 2

Tuesday, 10/13	
0800 - gathering & refreshments 0815 -	1040 - 12-Discovery Science - Reconnection - Will Fox (PPPL)
0830 - 08-Discovery Science - Accretion processes in astrophysics - Michel Koenig/B. Albertazzi/Emeric Falize (Ecole Polytechnique) (B. Remington to present) 0850 - 09-Discovery Science - Collisionless Shocks: PIC simulations of MiFEDs experiments - Federico Fiuza (Stanford) for Anatoly Spitkovsky (PPPL) 0910 - 10-Discovery Science - Fermi acceleration - Gianluca Gregori (Oxford) (Hye-Sook Park to present)	1100 - discussion plasma physics 1130 - 13-Hui Chen (LLNL) - positron trapping -
0930 - discussion re. laboratory astrphysics 1000 - break	1150 - discussion of contributed topics
1020 - 11-B-Field Generation at LFEX - Shinsuki Fujioka (ILE) (John Moody to present)	1230 - Wrap up/path forward/action items - All 1300 - adjourn

Basic B-field physics considerations

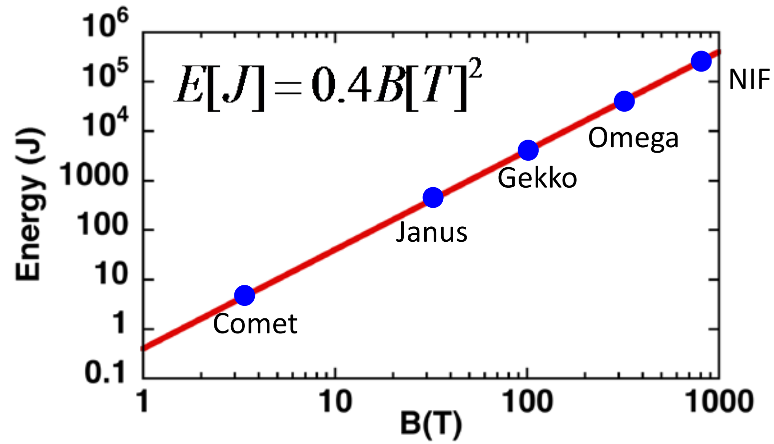
Soak-in time (1D in r)



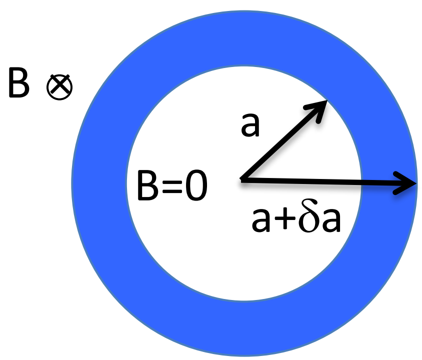
$$\tau = \frac{\mu_0 \sigma a \delta a}{2}$$

For Au, a = 5 mm,
δa = 30 μm:
τ = 3.9 μs

B-field energy in 1 cm³

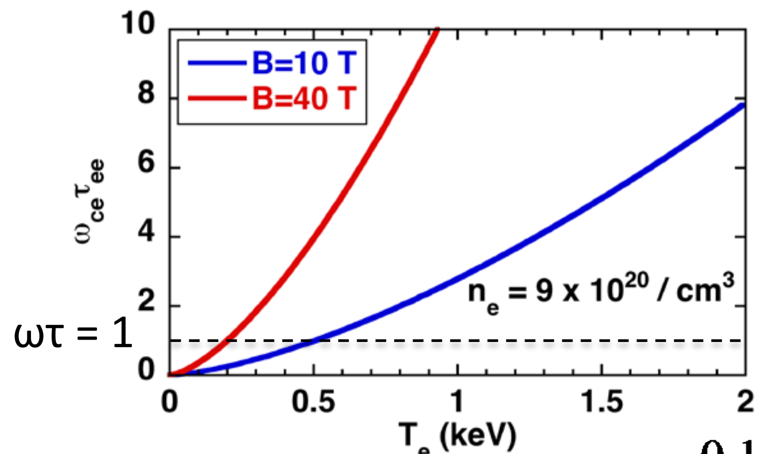


B-field pressure (1D in r)



$$P[bar] = 3.9 B[T]^2$$

Hall parameter



$$\omega\tau = 0.278 \bullet B[T] \bullet T_e[keV]^{3/2} \bullet \frac{0.1}{n_e / n_{cr(3\omega)}}$$

2 page Physics summary (1)

Experiment(s): Magnetized Ignition and TN-Burn Platforms

Experiment: *Magnetized ignition and TN-burn*
Responsible Org: *LLNL (LLE)*
NIF shots from: *ICF and HED programs*
Designers: *J.Perkins et al.*
Shot RI: *TBD* **Engineer:** *TBD*

Experimental objectives: Increase margin for ignition and TN-burn through capsule compression of an imposed magnetic field

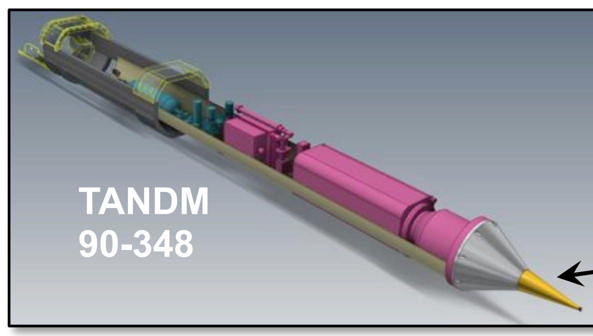
Key physics related to having a B-field: Lower required rhoR*$T_{hotspot}$ (P*tau) for ignition via reduction in alpha deposition range, suppression of e-heat conduction and suppression of hydro instabilities

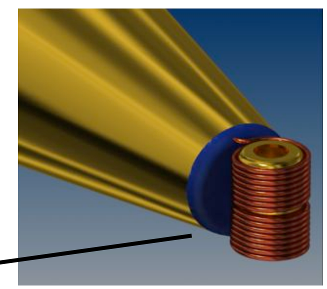
Expected results: Increase in (1) capsule fusion yields , (2) ignition onset, relative to corresponding controls with no applied field

⇒ May permit the recovery of ignition, or at least significant fusion alpha particle heating and yield, in otherwise sub-marginal NIF capsules

Important aspects of the experiment:

- **Key B-field requirements:** ~30-70T (~50T nominal), axial field within a hohlraum volume (~0.6x1.2cm); ≥1μs rise, Uniformity ~10% across capsule
- **LDRD-funded pulsed power system:** Can be ready for NIF integration in 2016 for room temperature targets (cryo-targets ≥2107)
- **Can be phased :**
  - 30-70T
  - Room-temperature targets then cryo



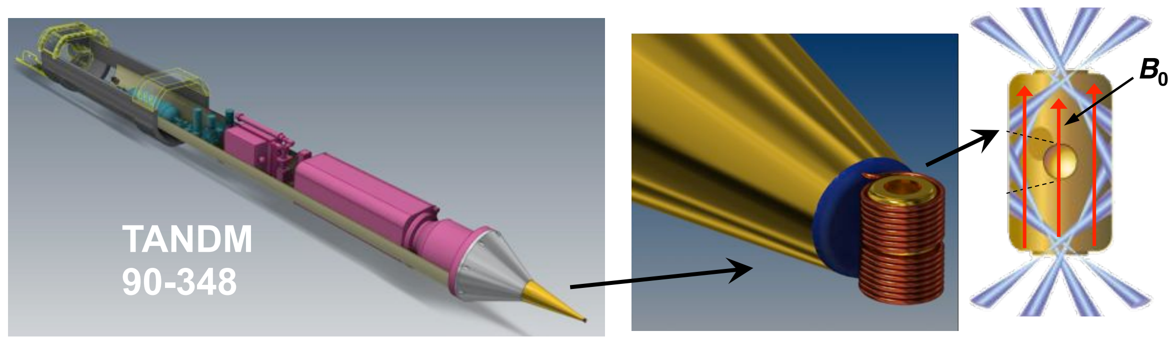


We have designed various magnetized ignition targets. First experiments will be room temperature gas targets

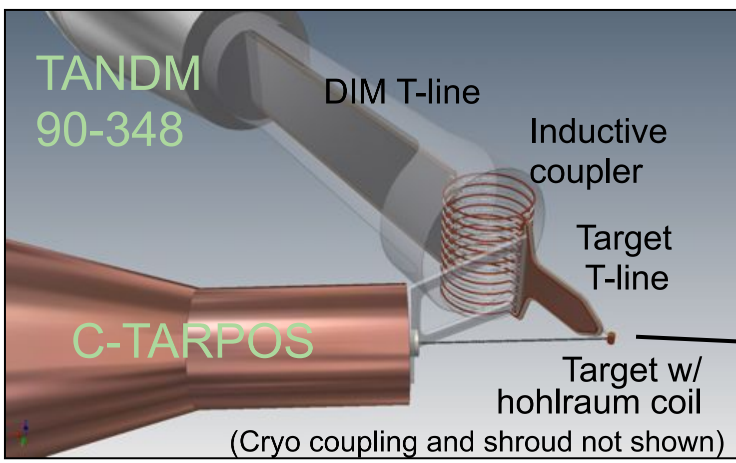
2 page Physics summary (2)

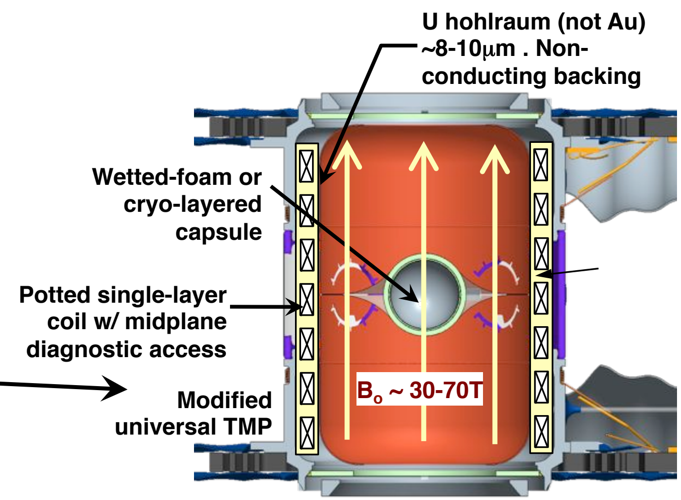
Experiment(s): Magnetized Ignition and TN-Burn Platforms

Pulsed power supply in TANDM 90-348 ?? (has alignment capability)



First experiments will be magnetized room-temp gas capsules (two variants). Shot from TANDM 90-348?





Cryo ignition targets (wetted-foam or cryo-layered) require TL-coupling to cryo-TARPOS)

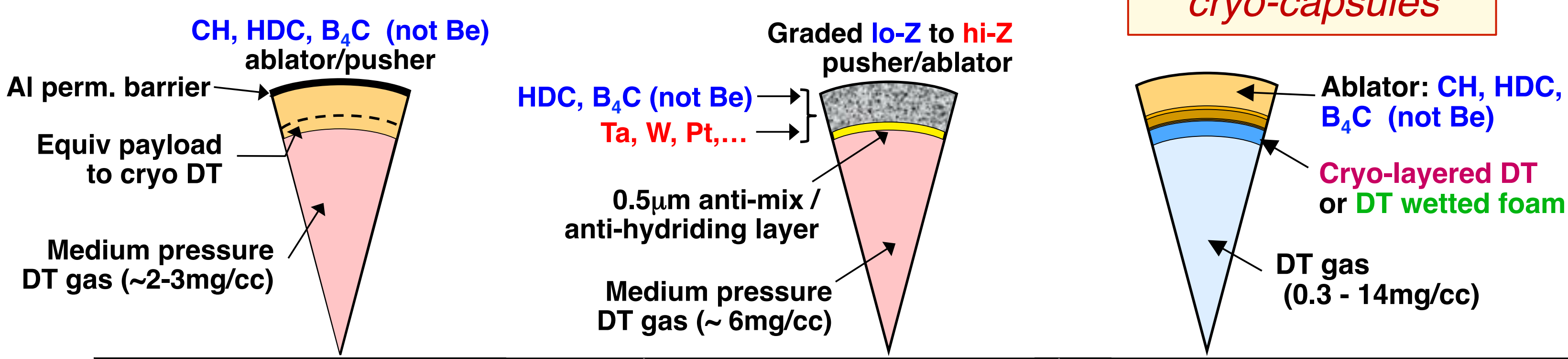
Magnetized Ignition and TN-Burn Platforms

Three classes of NIF magnetized ignition/burn platforms are under study in indirect drive

LDRD Laboratory Directed Research and Development

Magnetized room-temp. gas capsules for first experiments

Follow-on cryo-capsules



	Room-Temp Gas	Metal-Gas	Cryo Ignition
Rationale	B-dep. α heating feedback on yield (room-temp analog of cryo)	Volumetric ign/burn at T_{ign}~6keV with low velocity; other apps	Ignition and propagating burn at reduced hotspot conditions
Max yields (MJ)	~0.1	$\gtrsim$1	~1-20
Initial temperature	300K	300K	Cryo-layered ~19K Wetted foam: ~19-30K
DT Fuel	Gas (~10-15Atm, ~2-3mg/cc)	Gas (~29Atm, ~6mg/cc)	Solid-DT or wetted foam
Ignition type	Volumetric heating	Volumetric ignition	Hotspot ignition + prop burn
T_{i_ign} / T_{i_max}(keV)	Likely only α heat. to <10keV	~6 / 20 (Rad. trapped)	~12 / 100

Requirement: **B-field magnitude**

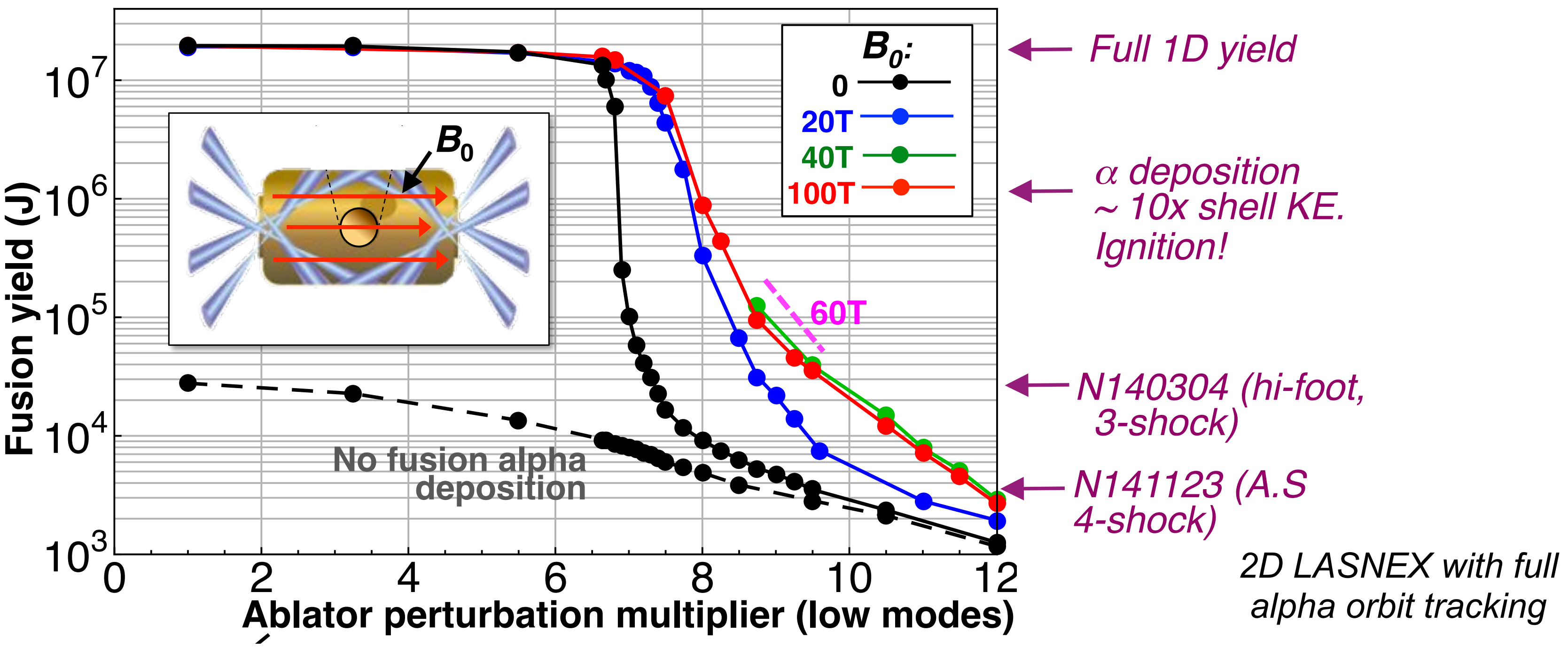
2015 NIF B-field Workshop

These experiments require B ~ 30-70T

B-field magnitude: 30-70T (50T nominal)

B-field spatial variation requirements: Solenoidal axial B_z field

B-field spatial uniformity requirements: Acceptable field uniformity across capsule (~10%) achievable from hohlraum solenoid w/ split coil and midplane diagnostic acc

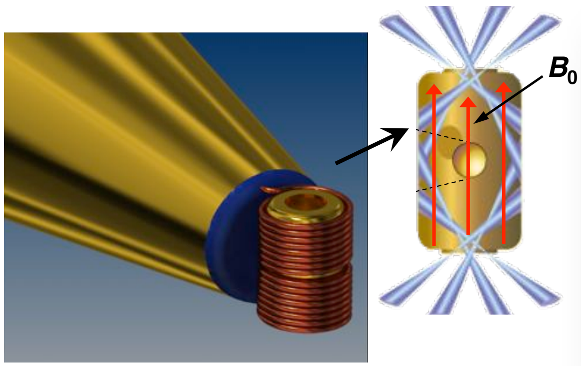


NIF cryo-layered ignition capsule; 4-shock 1.8MJ – An axial seed magnetic field may recover ignition, or at least significant alpha heating

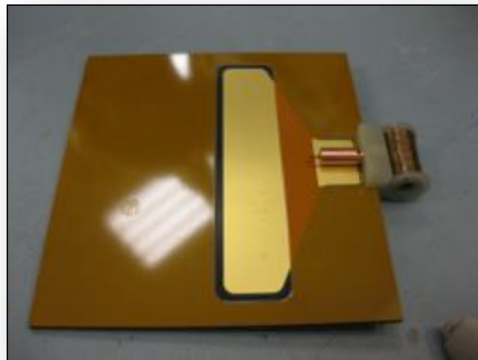
Requirement: **B-field spatial extent + diagnostic access**

2015 NIF B-field Workshop

Experiments require an axial hohlraum field with regular hohlraum diagnostic access

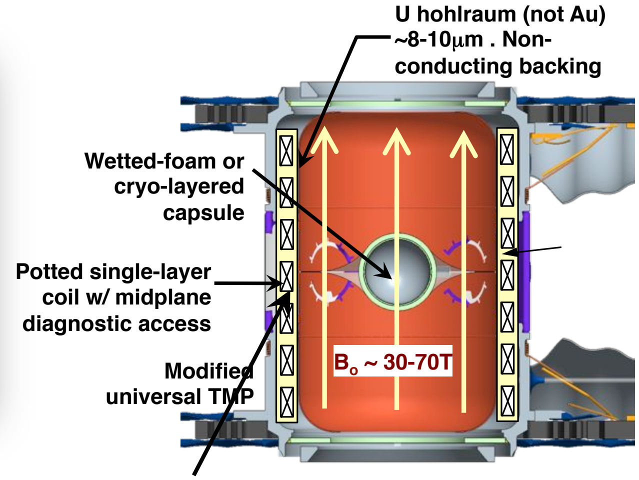


- Split, center-fed coil.
- 2dConA backlighter access 800x800μm.
- 1d self-emission access160x970μm
- Zylon composite overwrap
- No keyhole shots req'd



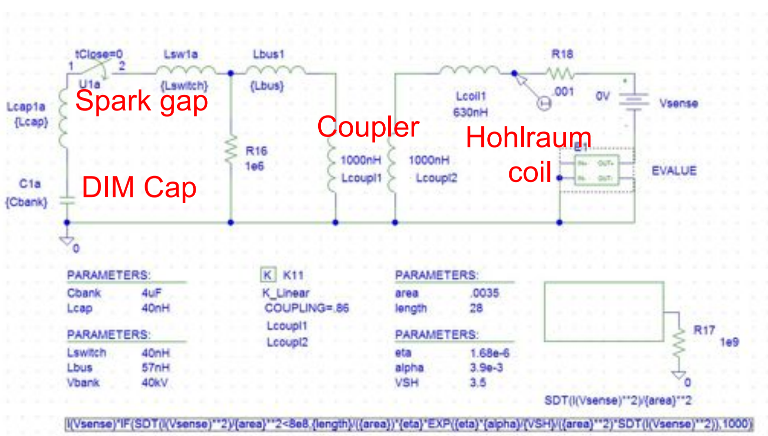
Hohlraum test coil

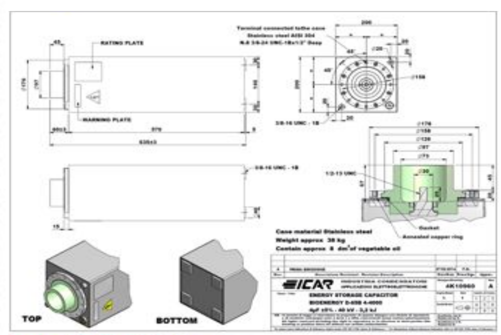
Room temperature targets



- 1d self-emission160x970μm
- No starburst if wetted foam

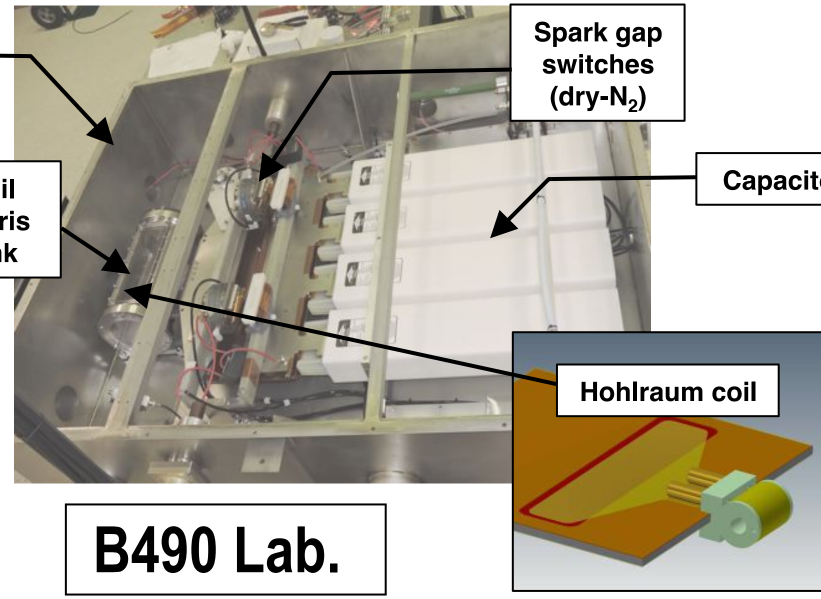
Cryo targets will require a modified TMP (no conductors outside the hohlram wall) and new cryo-shroud



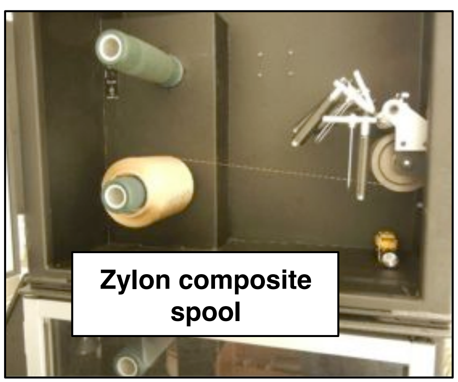


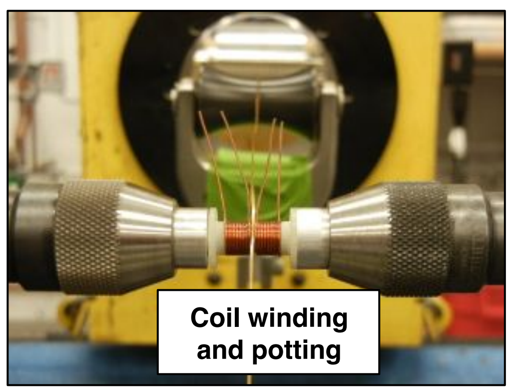
Pulsed power supply: ICAR has supplied us five spark-gap-switched capacitors ~4μF @40kV (3.2kJ), 60kA

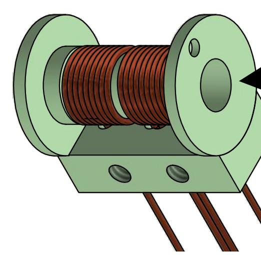
We are performing power supply and hohlraum coil tests in our B490 lab. Coils are wound and potted in B321



B490 Lab.

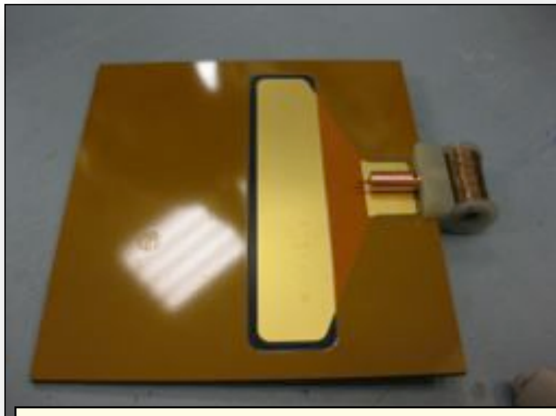




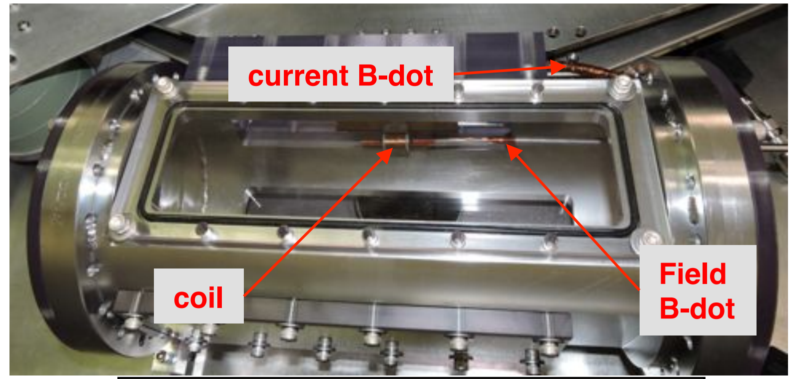


B321 Winding Facility

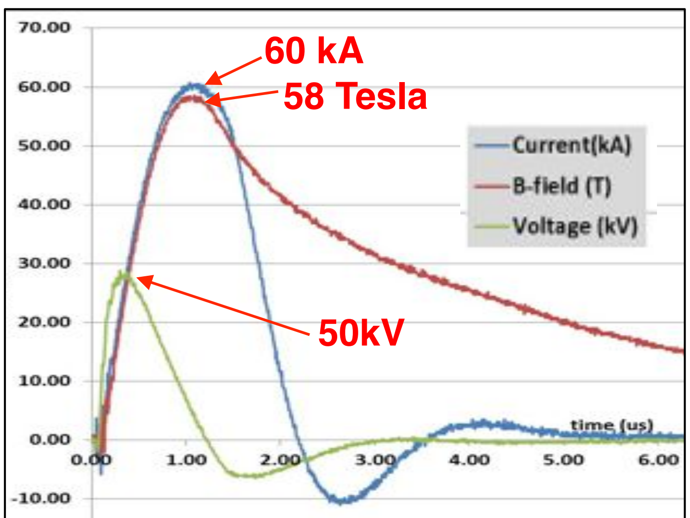
Design field for NIF hohlraums =50T nominal (70T max). We've achieved 58T in our offline lab tests in sample hohlraum coils



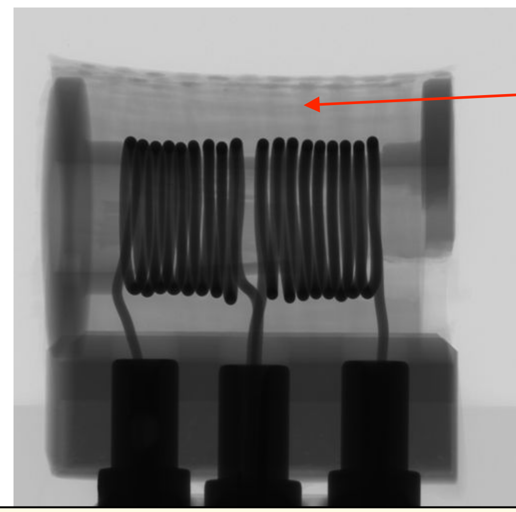
Wound potted coil and T-line



Coil mounted in debris tank



Waveforms – latest 58T shot



Coil after a 31T shot

Tensile strength of Zylon composite ~ 5800 MPa.

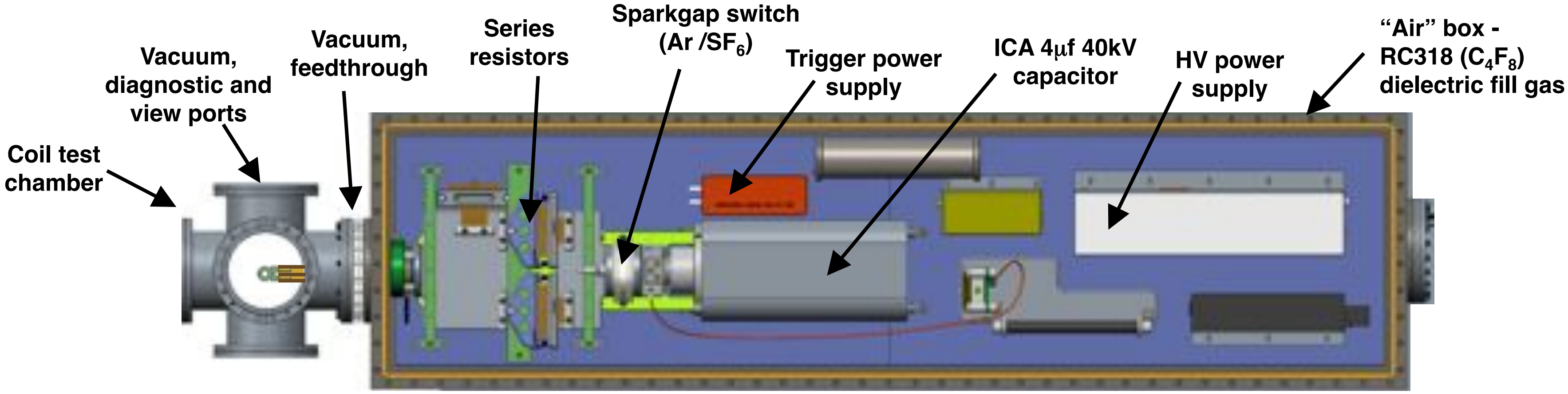
Tube stress at 50T ~1600MPa.

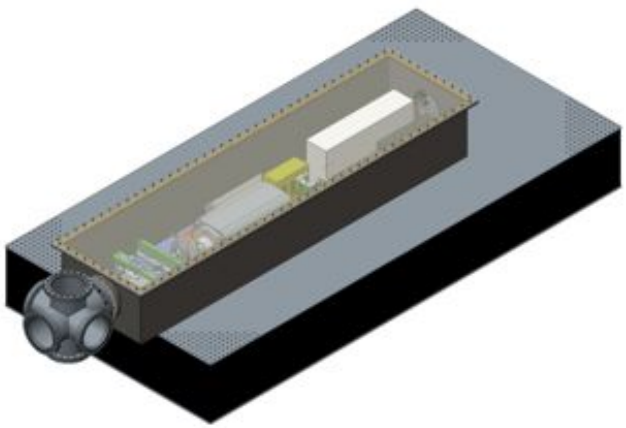
So shouldn't disassemble

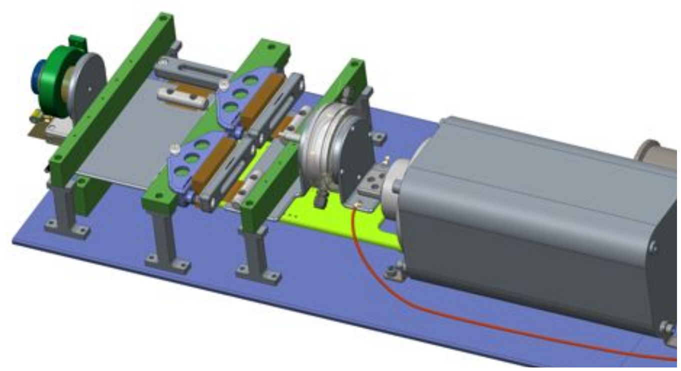
(ALE3D suggests no melt at 50T, 70% of melt at 70T but after peak field is reached)

M.A.Rhodes *LLNL*

A new test tank with NIF-integrable components is under construction for vacuum coil tests this fall in our B490 lab.







We are liaising with NIF to assess 2016-17 integration.
The NIF FY16 new experimental capabilities program contains a line item for this (NNSA MTE 10.3 - NIF Diagnostics, Cryogenics, and Experimental Support)

M.A.Rhodes *LLNL*

Requirement: **B-field rise-time**

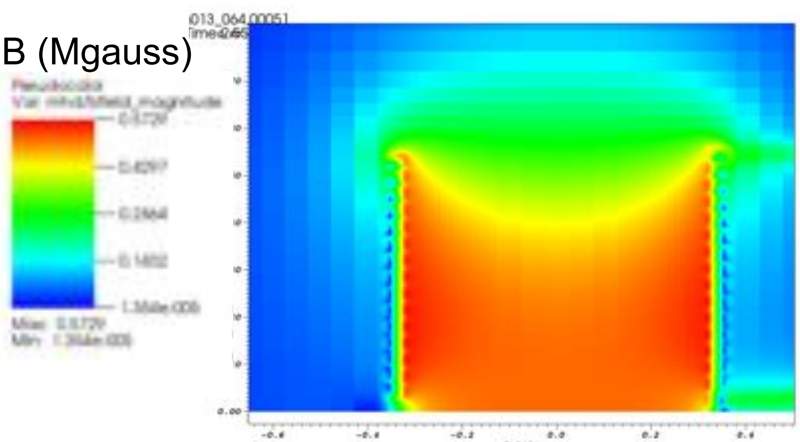
B-field rise-time and flattop requirements

B-field requirements: B-field to be established before, and maintained during, capsule implosion, i.e., time constants >>20ns

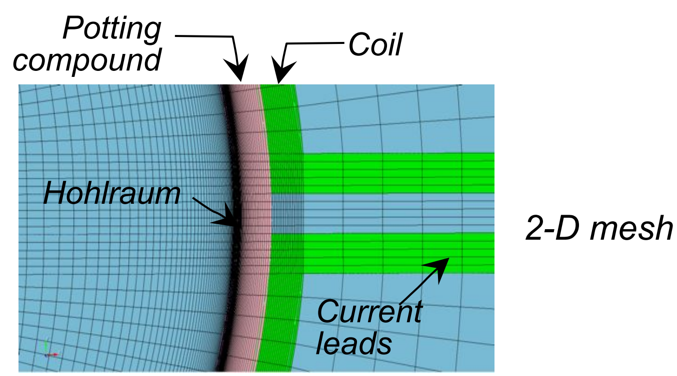
B-field rise-time: • Sufficiently slow to minimize dB/dt effects in 8-10μm U hohlraum • ⇒⩾1μs (present design is ~2μs); • Can't be >> than this otherwise coil will melt before peak field; • Au hohlraum likely too conductive; • Effect on cryo-layering TBD (→ baseline wetted foams for first cryo tests)

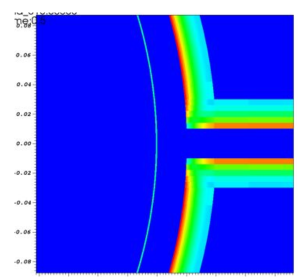
B-field "flattop": 500ns for ≥90% of field. (present sinusoidal design field half (+ve) period ~ 4μs)

ALE3D:
3D MHD simulations

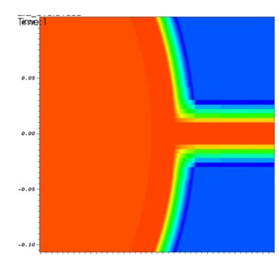


*Hohlraum field at 2.5μs for 38 kA into 2*15-turns => 50T*





Current density at ~0.5μs (note skin effect)



Magnetic field at peak current ~constant inside for U-hohlraum

Other issues:

Capacitor stored energy in TANDM: 3.2kJ at full charge. Shrapnel case and debris containment? Can it survive gas box depressurization? (Alternative external cable current-supply system?? – we scoped this and discarded in favor of the present in-situ design)

Laser pulse shape and protection: All magnetized ignition target designs thus far have conventional 2-4-shock adiabat-shaped pulse shapes so laser considerations are ~same as for regular targets
(However, stay tuned for a left-field concept….!)

EMP: Lots of gammas (→Compton electrons) in a compressed magnetic field – especially for the metal-gas targets; ⇒ Diagnostics protection?

dB/dt: Effect of dB/dt on cryo-layering TBD (⇒ baseline wetted foams for first cryo tests). Effects on U hohlraum modeled as ~OK but will be verified in lab tests in the near future

Vibrations: Effect of spark gap, cap and coil JXB pulses on alignment?

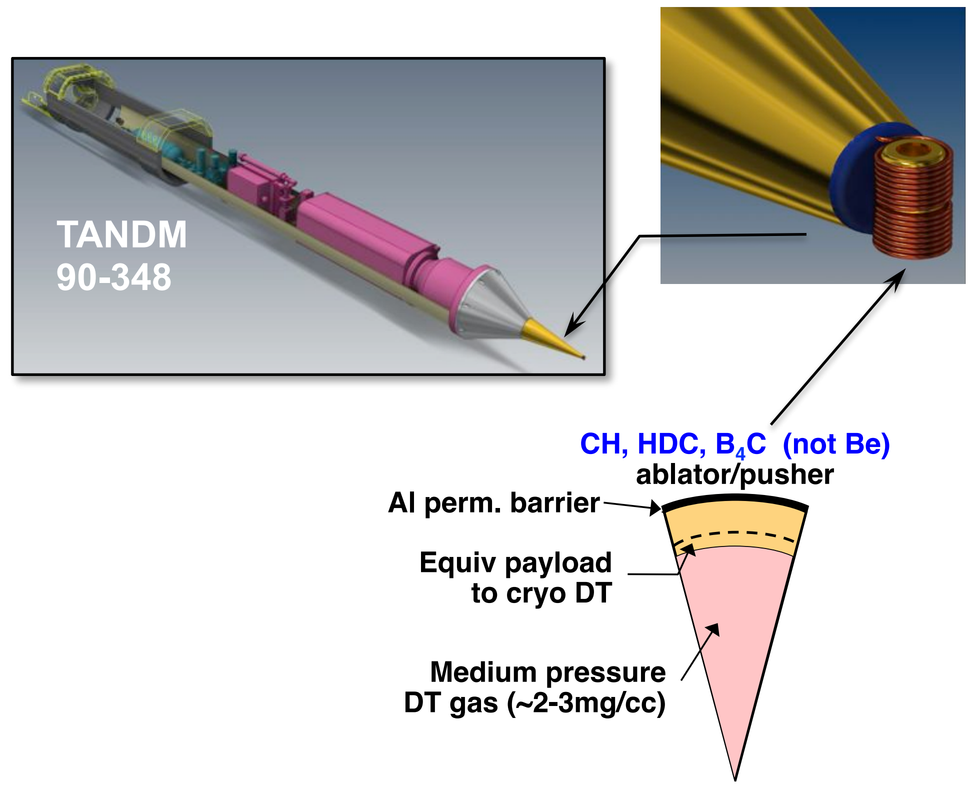
Coupling to cryo targets: We are assessing an inductive coupling concept from room-temperature TANDM T-line to cryo hohlraum+coil (other ideas ?)

Summary

Experiment(s): Magnetized Ignition and TN-Burn Platforms

<u>Summary requirements</u>

B-field magnitude	30-70 T
B-field spatial shape / extent	Axial solenoidal field within a NIF hohlraum volume
B-field uniformity	~10% over capsule volume
B-field rise time	≥1 μs
Diagnostic access	Regular NIF requirements for 2dConA, Symcaps and cryo (no keyhole req'd)
Other	Future coupling to cryo capsules



Room temperature magnetized gas target

This NIF magnetized target capability would enable a rich portfolio of discovery science and HED applications. Examples…

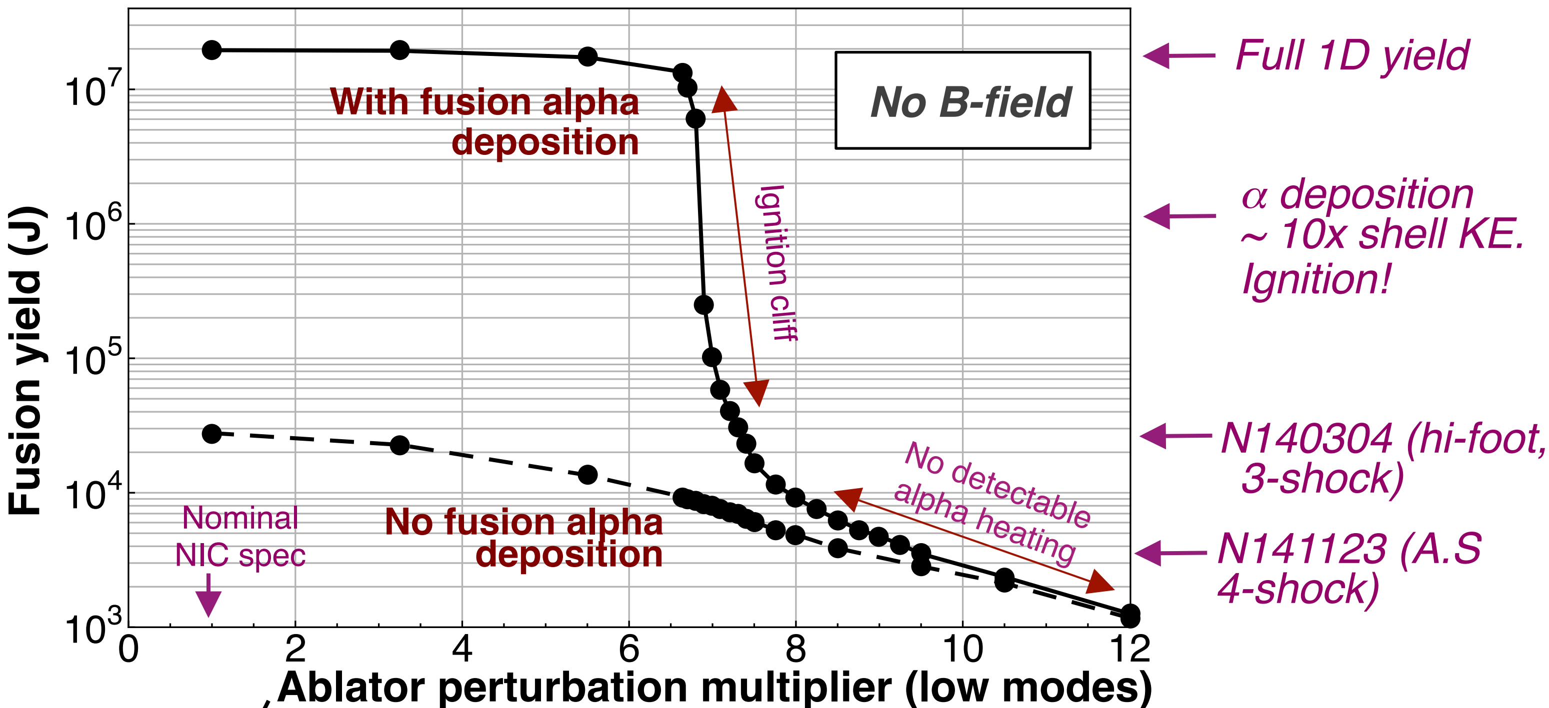
LDRD Laboratory Directed Research and Development

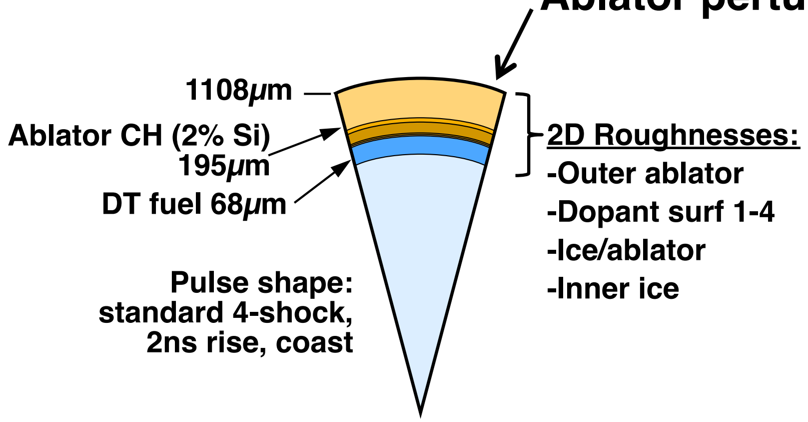
- **Ignition and TN-burn in magnetized capsules (various types) - enhancement of ign. margins:** *~50T, hohlraum volume, room temp and cryo capsules, ≥1MJ*
- **Validation of laser preheat in magnetized channels for application to Sandia's MagLIF initiative:** *~30T,1cm-length, gas channel, 30kJ*
- **Collisionless shocks in background fields (gamma-ray bursters, supernova remnants):** *~30T+, 1cm, D_2-CH low-density plasma, 1cm-length (0.3cm access) 250kJ*
- **Magnetic stagnation of plasma flows (solar-terrestrial magnetosphere, heliosphere), instabilities and inhibition.** *Need $B^2/2\mu_0 \sim \rho v^2$.*
- **Astrophysical jets (accretion columns, white dwarfs):** *10's-T, 0.25n_{crit} doped neopentane, nozzle-LEH for high Mach-No., ≥1MJ*
- **High T_{rad} hohlraums: high intensity beams in small volume hohlraum with B-suppression of e-transport in hi-Z non-LTE conversion layers:** *~10'sT, 80μm beam spots ~10^{16}W/cm^2 (no phaseplates)*
- **High altitude phenomena:**
  - **Exploding plasma collisionless shocks**
  - **EMP E1 (WEMP code benchmarking):** *~20T, $\rho R_{gamma\text{-}absorber}$~1gm/cm^2, ⇒100 Compton gyro orbits, e-mfp/gyro orbit ~1/3 (EMP from compressed capsule burn?)*

⇒ Applications require ~10's T in ≲cm^3 volumes, so all are potentially appropriate experiments for this system

Backup Slides

NIF cryo-layered CH ablators: Increasing capsule perturbations will cause ignition failure

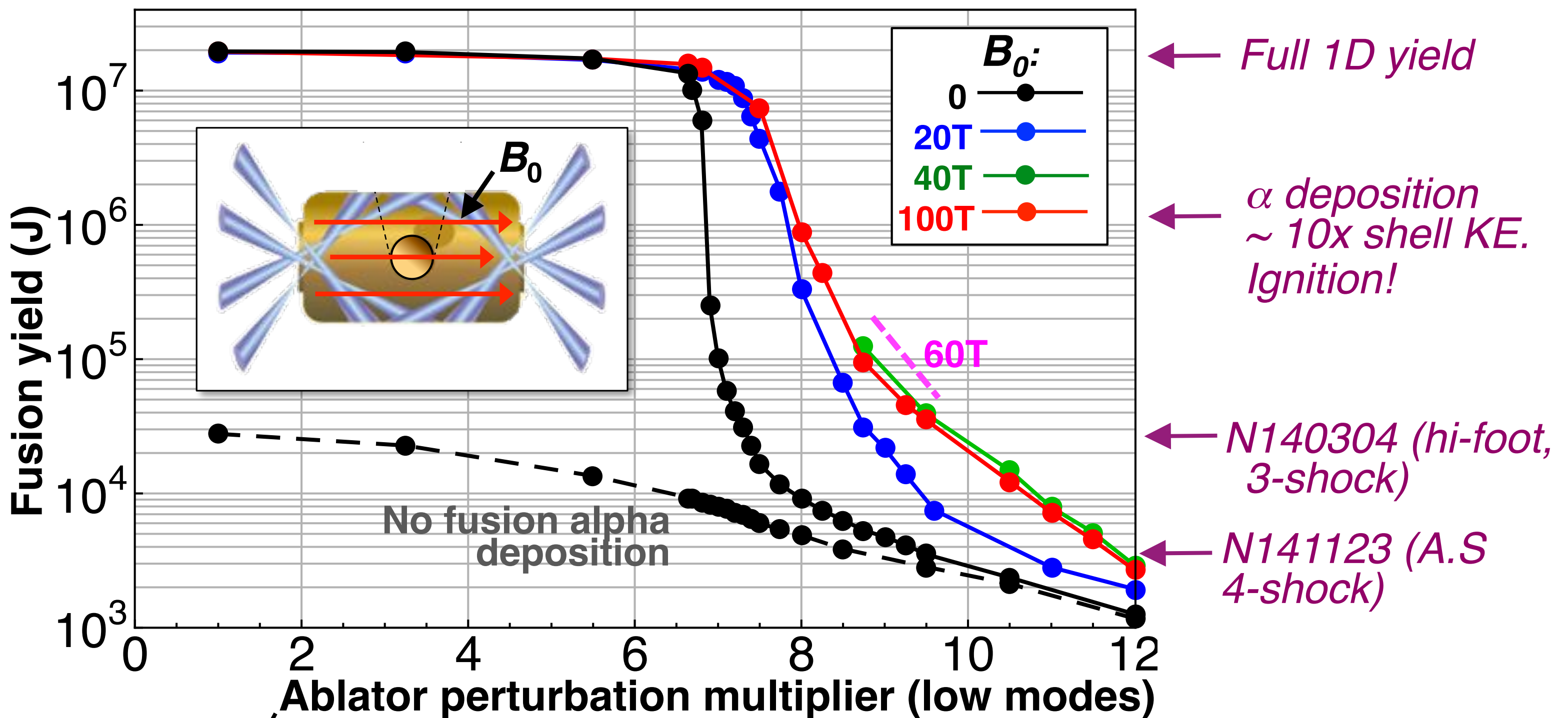


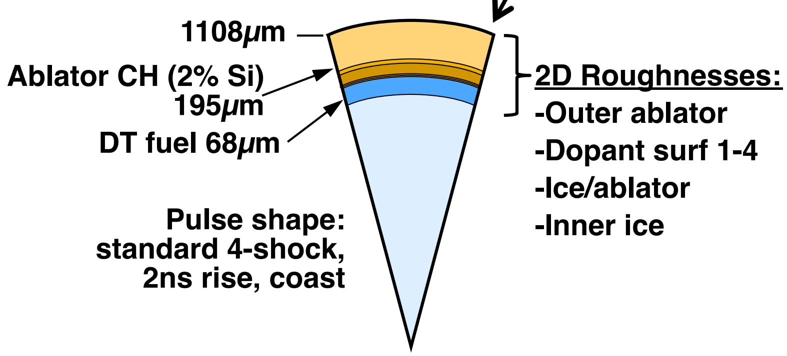


2D LASNEX simulations

Standard NIC CH-abl. 2%Si(X1) 68μm fuel, low foot 4-shock

An axial seed magnetic field may recover ignition, or at least significant alpha heating

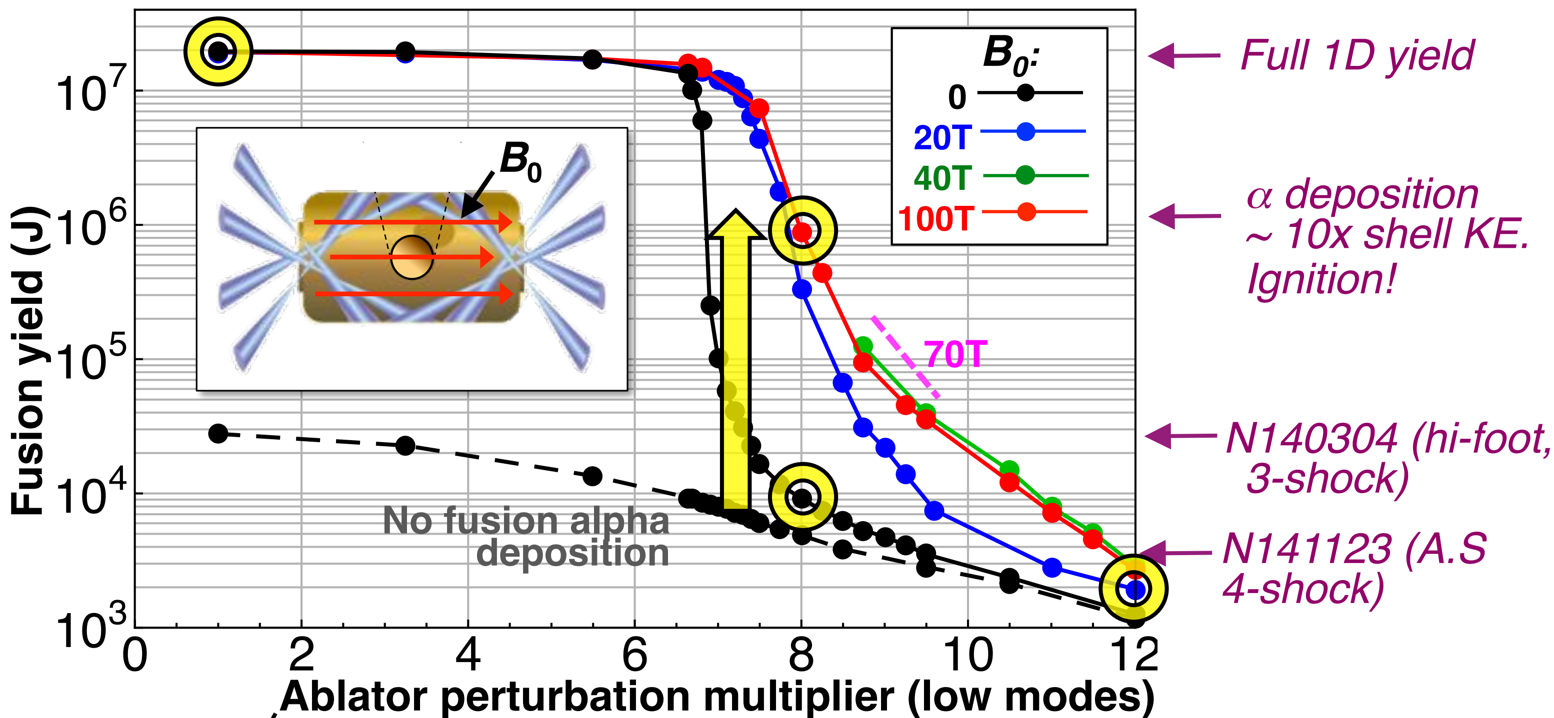


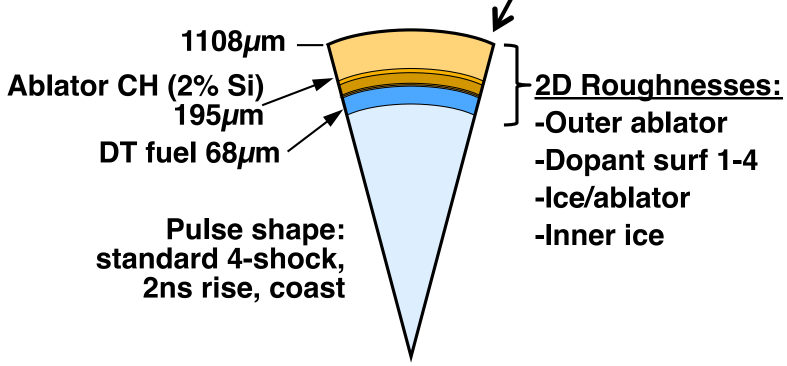


2D LASNEX simulations with full orbit following of fusion alpha particles

Standard NIC CH-abl. 2%Si(X1) 68μm fuel, low foot 4-shock

An axial seed magnetic field may recover ignition, or at least significant alpha heating



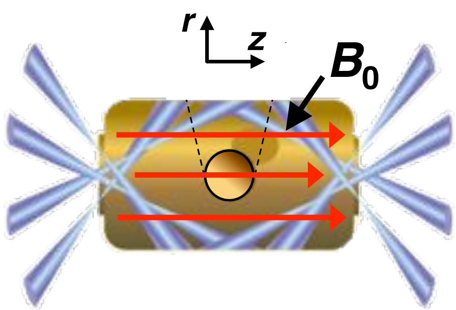


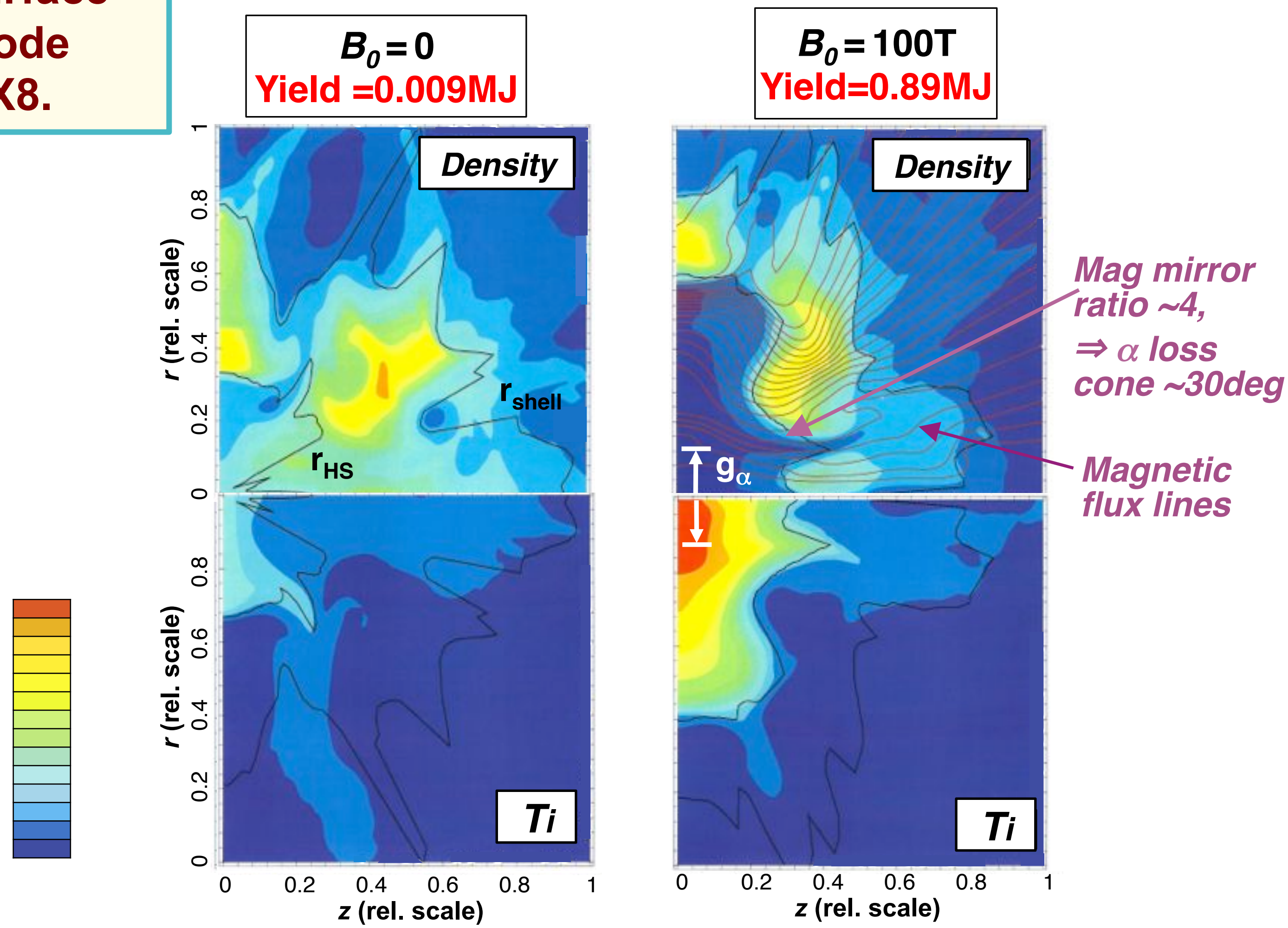
2D LASNEX simulations with full orbit following of fusion alpha particles

Standard NIC CH-abl. 2%Si(X1) 68μm fuel, low foot 4-shock

LASNEX simulations indicate that imposed fields recover ignition in otherwise sub-marginal capsules

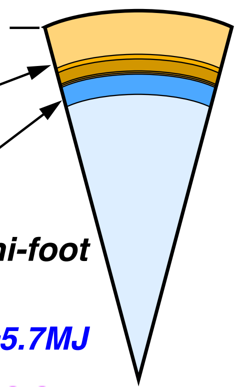
Contours at ign/stagnation for a large outer surface amplitude low-mode perturbation of X8.





NIF cryo CH capsules: What does a compressed B-field do for a 3-shock Hi-Foot implosion?

Apply angle-dep. P4 rad flux perturbation to approx. match N140304 3-shock hi-foot inflight + stagnation params

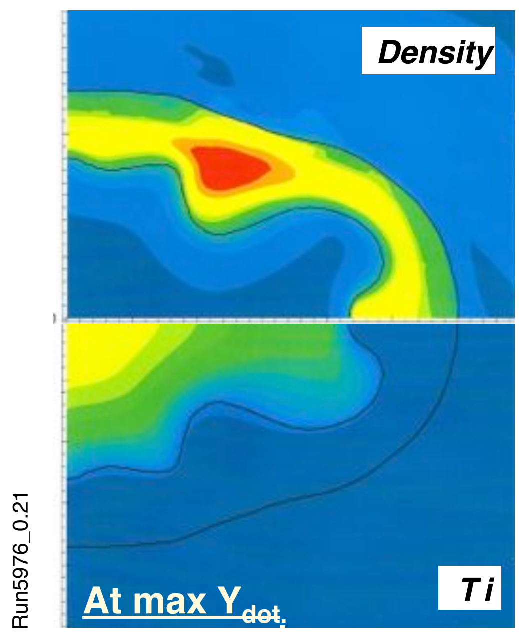


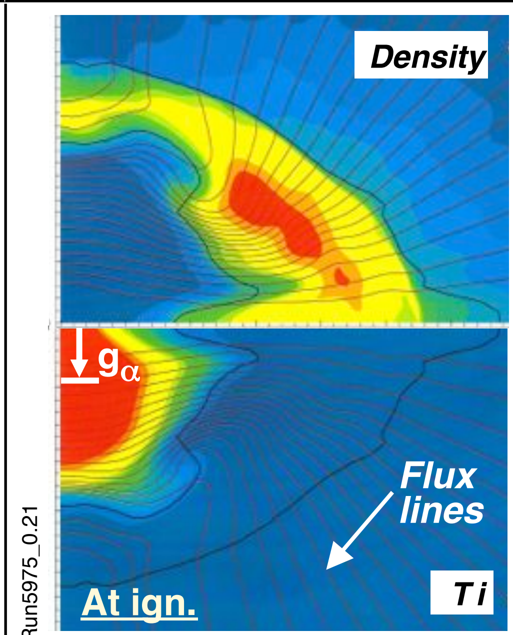
<u>N140304 Hydro Parms:</u>

442TW, 1.86MJ, 3-shock hi-foot

V =3.7e7cm/s, α =2.42

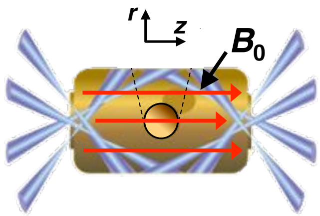
2D x1 rough. fusion yield=5.7MJ



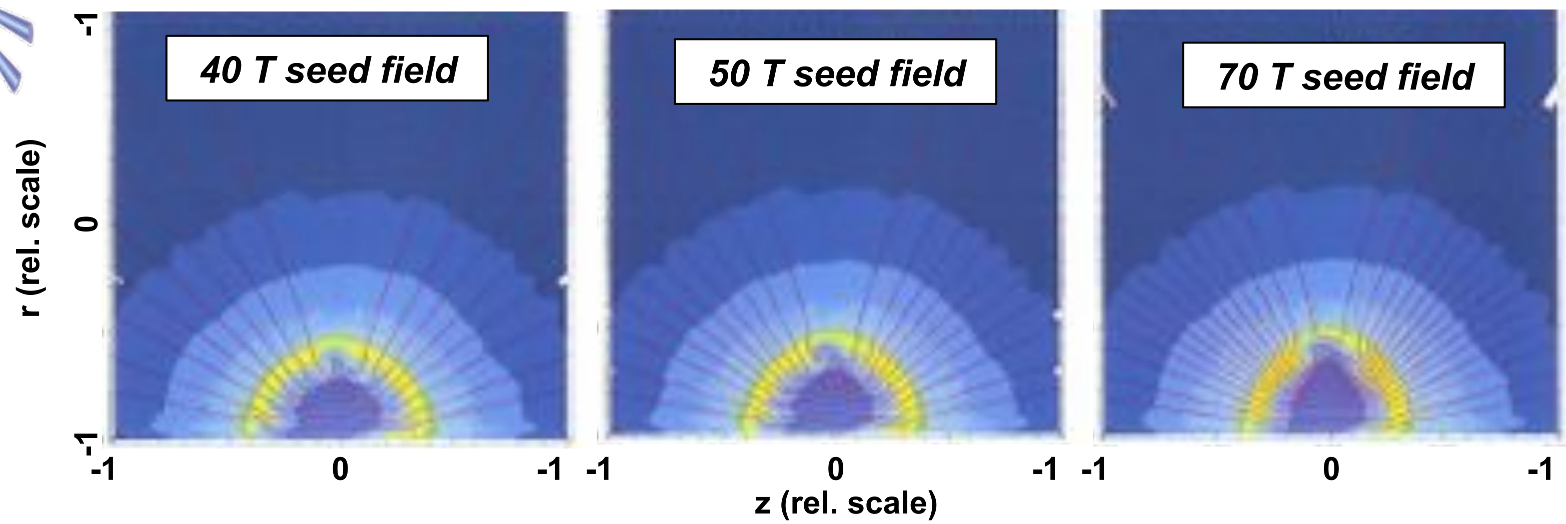


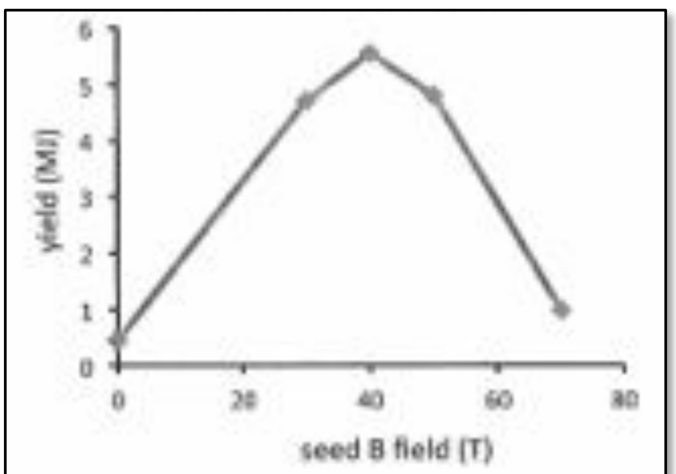
	N140304 Data	2D Perturbed. No B	2D Perturbed. B_0=50T
Fusion yield	N_n=9.43e15, 26.6kJ	N_n=**8.88e15, 25.1kJ**	N_n=**8.49e16, 240kJ**
Ti_Brysk (keV)	5.55 (Incl Doppler?)	3.62	9.50
Ti(0) max (keV)	–	6.64	15.0
$\rho R_{hs}/\rho R_{shell}$	0.140/0.775	0.338/0.740	0.266/1.13
P_{hs} (Gbar)	173	221	349
Conv. ratio	33.5	33.0	37.1
Yield–no α dep.	12.3kJ	11.6kJ	14.9kJ

NIF 3-shock cryo-HDC capsules: Implosion departs further from sphericity as seed field increases beyond ~40 T



HDC 3-shock: Density contours @ignition



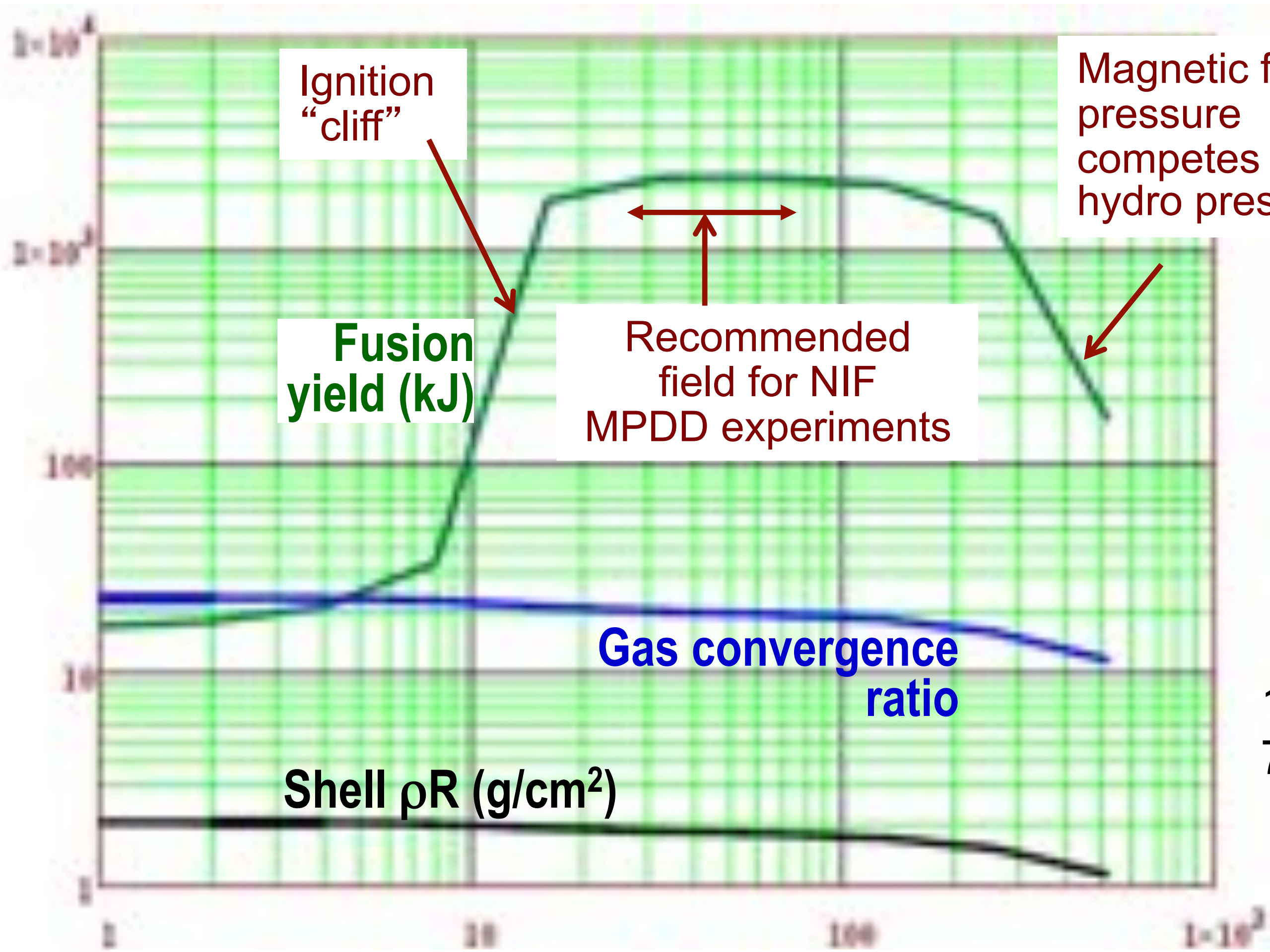


- HDC 3-Shock. Nominal roughness -

Optimum seed field for an HDC 3-shock capsule is around 40T

D.D.Ho *LLNL*

NIF Polar Direct Drive with magnetized HDC gas capsules (B. G. Logan)



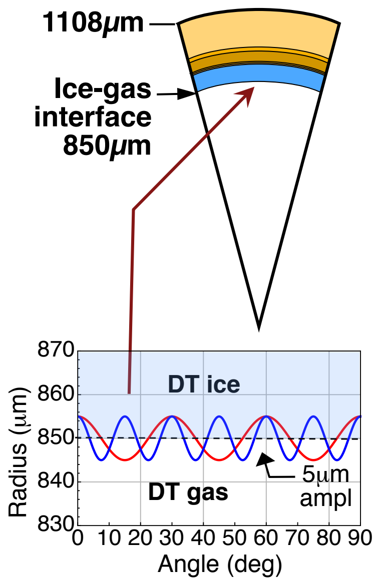
Initial applied magnetic field B_{zo} (T)

190km/s,
7.9mg/cc fill

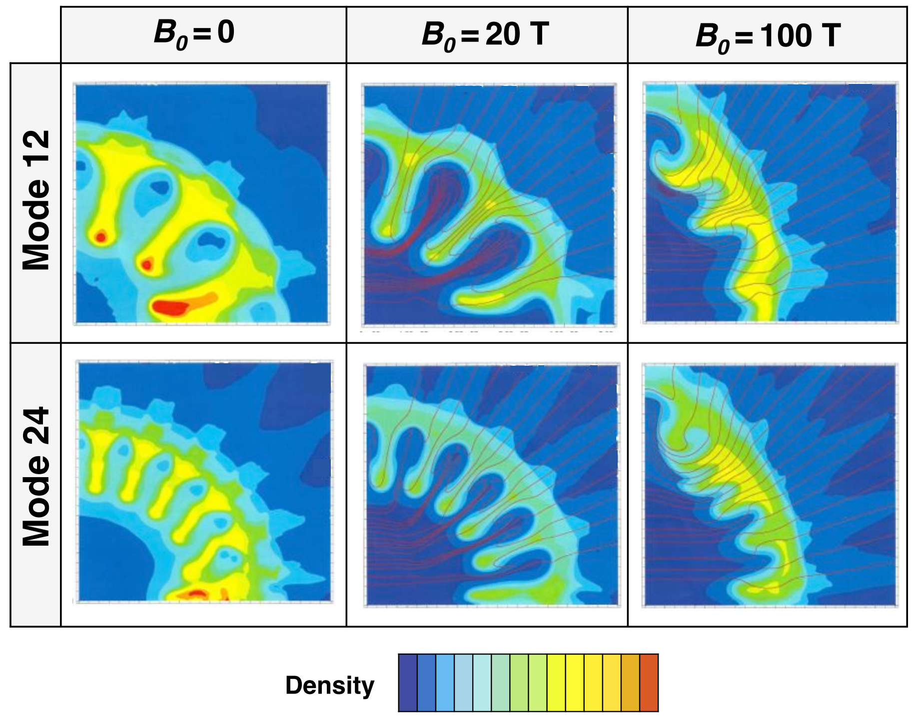
HDC room temperature gas capsule in polar direct drive have the potential for over 1MJ yield with an imposed magnetic field

Simulations indicate that RT-growth into the hotspot may be suppressed at higher B-fields (in 2-D at least)

Density contours in the r-z plane at ignition (T(0)=12keV) for imposed single-mode perturbation of amplitude 5μm on ice-gas interface at t=0



Impose a 5μm amplitude ℓ=12 and ℓ=24 cosine initial perturbation on ice-gas interface at t=0



Suppression of RT instabilities is due to the field-line bending energy that must be expended (good curvature direction → stabilizing).

Effect will be enhanced at higher mode numbers (smaller bend radii) but 3-D simulations will be required for full insight

The rich physics of NIF magnetized ignition targets – Findings to date….

LDRD
Laboratory Directed Research and Development

- Initial fields of 40-70T compressing to >10^4 T (100's MG) under implosion can relax conditions for ignition and thermonuclear burn in NIF targets (hotspot-ignition and volumetric-ignition target variants)
- Trapped alpha particles are localized within hotspot resulting in reduced hotspot criteria for ignition (reduces required ρR*T and pressure for ign)
- Electron heat conduction loss in hotspot is shut off across the field ($\omega_{ce}\tau_{ei}$>>1)
- Mirror fields in sausage implosions provide further insulation to electron and alpha conduction loss (as could frozen-in field lines spun up by resid.-KE)
- Compressed field may suppress Rayleigh-Taylor instability ingress into hotspot during stagnation
- Imposed magnetic fields enable volumetric ignition/burn in room-temperature high-Z metal-gas targets (first experiments?)
- Hohlraum field can improve inner beam propagation and may inhibit transport of late-time LPI hot electron preheat to capsule

⇒ May permit the recovery of ignition, or at least significant fusion alpha particle heating and yield, in otherwise sub-marginal NIF capsules

Use of External Magnetic Fields in Hohlraum Plasmas to Improve Laser-Coupling

D.S. Montgomery, B.J. Albright, J.L. Kline, L. Yin
Los Alamos National Laboratory
D.H. Barnak, P.Y. Chang, J.R. Davies, G. Fiksel, D.H. Froula, R. Betti
Laboratory for Laser Energetics, University of Rochester
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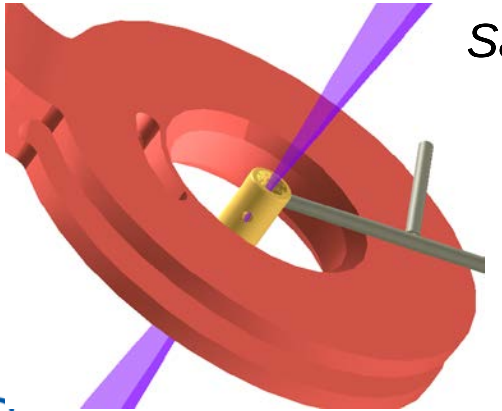

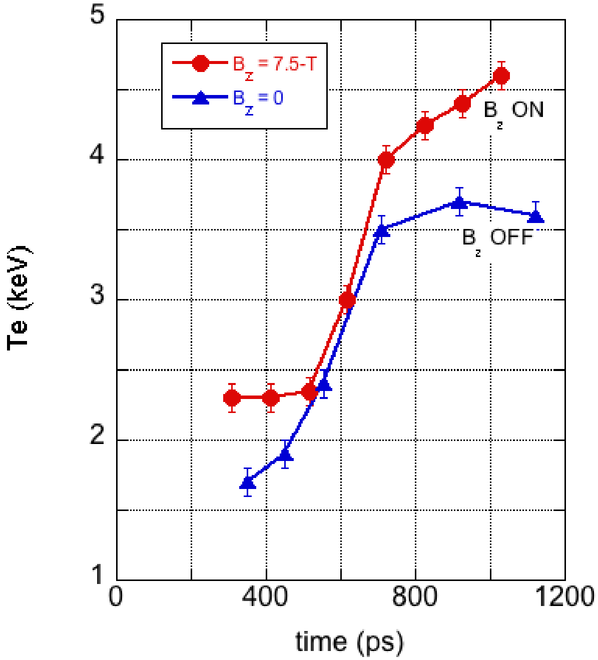

56th Annual APS-DPP
New Orleans, LA
Oct. 27-31st, 2014

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Use of External Magnetic Fields in Hohlraum Plasmas to Improve Laser-Coupling

- **Increased underdense plasma temperatures are desirable for NIF ignition hohlraums**
  - improve laser propagation through long-scale-length low-Z plasma (less inverse bremsstrahlung absorption)
  - possibly mitigate LPI with higher T_e (higher $k\lambda_D$, more Landau damping)
- **Magnetic insulation can increase the plasma temperature with $B_z \geq$ 10-T in gas-filled hohlraums**
- **Omega experiments using gas-filled hohlraums demonstrate an increased plasma temperature with B_z = 7.5-T**
  - plasma conditions measured with 4ω Thomson scattering
- **2-D HYDRA simulations are in good agreement with experimental results**

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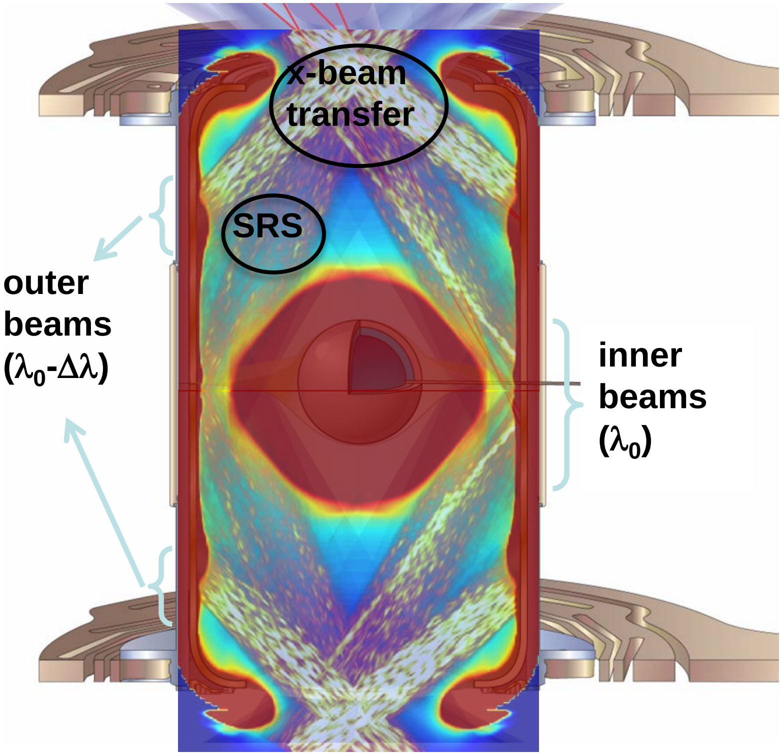
Adequate coupling of the laser is required for indirect drive ignition



- laser-hohlraum coupling affects:
  - radiation drive (implosion velocity)
  - radiation symmetry
  - preheat

- lower than expected T_e is inferred [1] in the underdense plasma for NIF ignition hohlraums:
  - significant collisional absorption in cooler, low-Z plasma (symmetry)
  - substantial SRS on inner beams (drive, symmetry, preheat, …)

Higher coronal plasma temperatures can improve laser-plasma coupling in hohlraum targets

1. M.D. Rosen *et al.*, *HEDP* **7**, 180 (2011)

SRS reflectivity decreases with increasing $k\lambda_D$ (increasing electron temperature T_e)

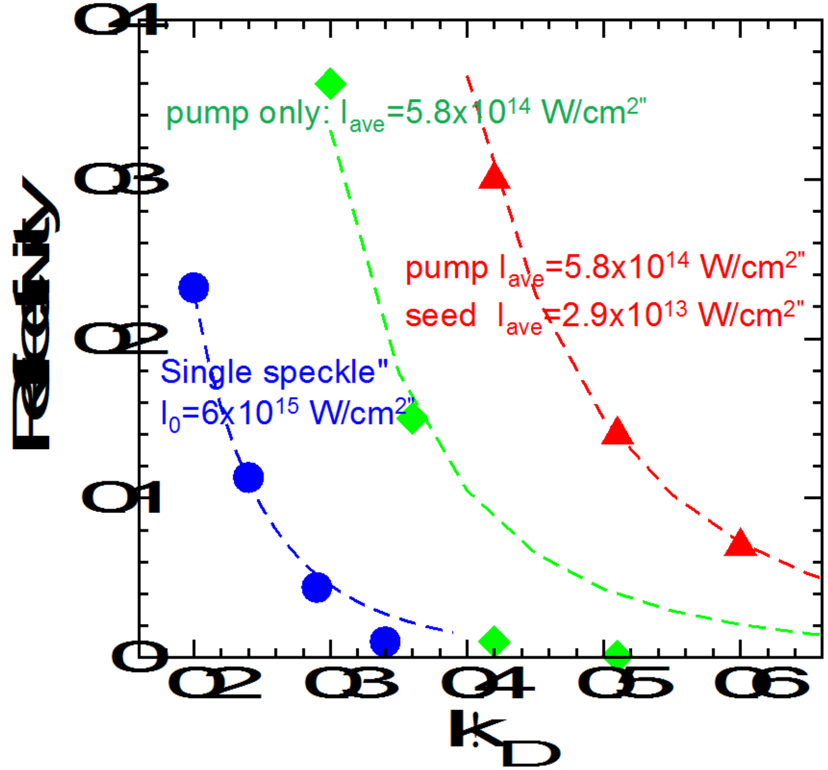
- The daughter EPW saturates when the trapped e- bounce frequency is comparable to the side loss rate for a trapped electron

$$\frac{\omega_b}{\omega_{pe}} = k\lambda_D\sqrt{\frac{e\phi}{T_e}} \sim \frac{\nu_{sl}}{\omega_{pe}}$$

- $E_{SRS} \sim \phi E_{laser}$; $R_{SRS} = (E_{SRS}/E_{laser})^2$, so

$$R_{SRS} \sim \frac{1}{(k\lambda_D)^4} \quad \text{(or } R_{SRS} \sim T_e^{-2}\text{)}$$

- This simple scaling[1] agrees well with both single- and multi-speckle VPIC simulations over a range of conditions



[1] Yin, Albright, Rose et al. *Phys. Plasmas* 19, 056304 (2012) !

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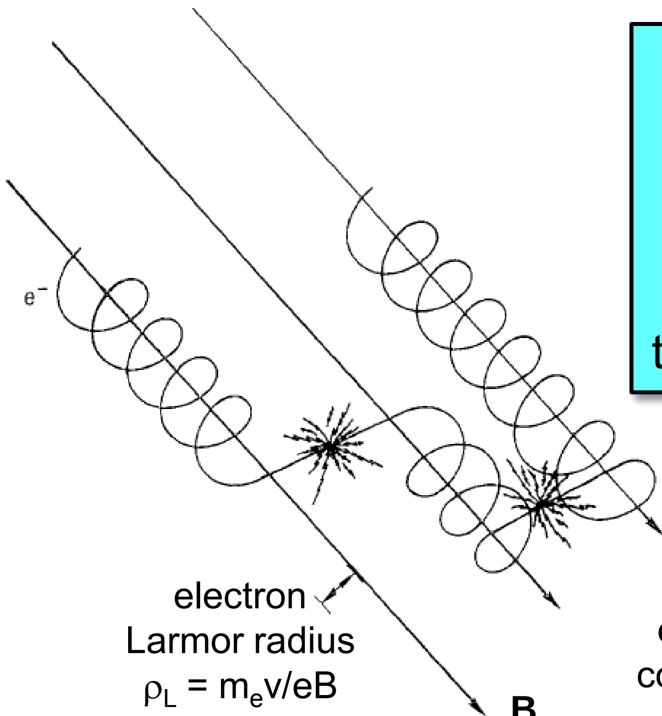
Magnetic insulation can lead to increased hohlraum plasma temperatures



when $\rho_L < \lambda_{ei}$ transport across magnetic field is reduced since ρ_L sets the transport step size

adapted from "Physics of Laser Fusion, Vol. 1", C.E. Max, UCRL-53107 (1982)

Braginskii heat flux†

$$Q_B \approx -\kappa_{\parallel}\nabla_{\parallel}T_e - \kappa_{\perp}\nabla_{\perp}T_e$$

$$\kappa_{\parallel} \approx \gamma_0 \frac{n_e T_e \tau_{ei}}{m_e}$$

$$\kappa_{\perp} \approx \gamma_1' \frac{n_e T_e \tau_{ei}}{m_e \omega_{ce}^2 \tau_{ei}^2}$$

"insulation" occurs when:

$$\frac{\kappa_{\perp}}{\kappa_{\parallel}} \approx \left(\frac{1}{\omega_{ce}\tau_{ei}}\right)^2 << 1$$

† ignoring cross-terms

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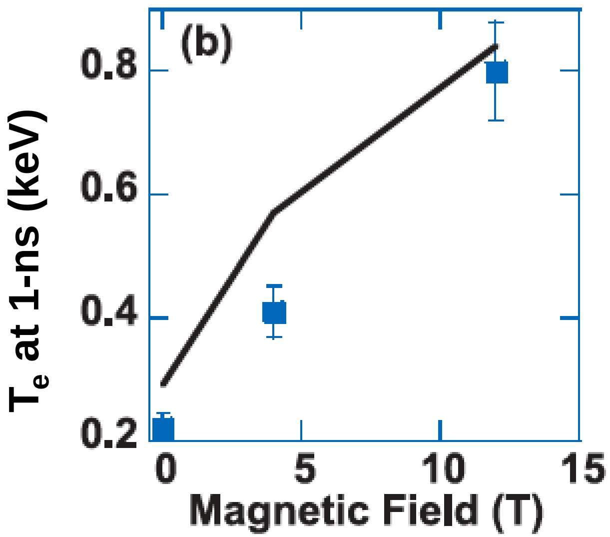
Scaling from previous experiments suggests B_z ~ 10-T may increase T_e in gas-filled hohlraums

Magnetized Gasjet Experiments*



* Froula *et al.*, *PRL* (2007)

	gasjet parameters	NIF parameters
T_e	250 eV	2 – 2.5 keV
n_e	1.5e19 e/cm^3	1e21 e/cm^3
Z	~ 5 (N_2)	2 – 3.5 (He or CH)
B_z	10 T	10-12 T
$\frac{1}{\omega_{ce}^2 \tau_{ei}^2}$	$\frac{\kappa_\perp}{\kappa_\parallel} \approx \frac{1}{15}$	$\frac{\kappa_\perp}{\kappa_\parallel} \approx \frac{1}{10} - \frac{1}{15}$

We expect a temperature increase for magnetized NIF hohlraums

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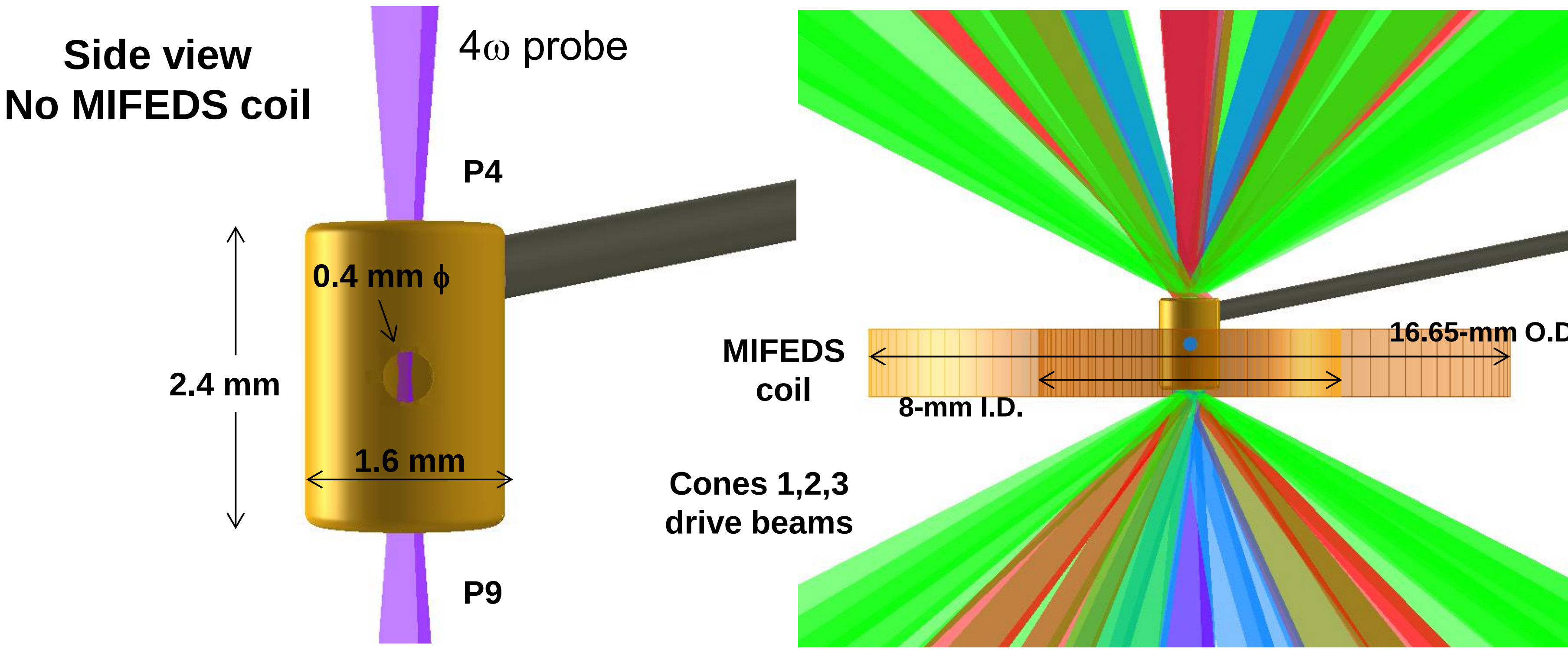
Experiments are performed at Omega using gas-filled hohlraums and an external B-field



- 19-kJ of 3ω in 1-ns pulse (39 beams, 3 cones), gas-fill 0.95-atm 25% C_5H_{12} + 75% CH_4
- plasma conditions measured using 4ω Thomson scattering, delayed 0.3-ns
- external B_z applied using MIFEDS coil in a 400-ns pulse†

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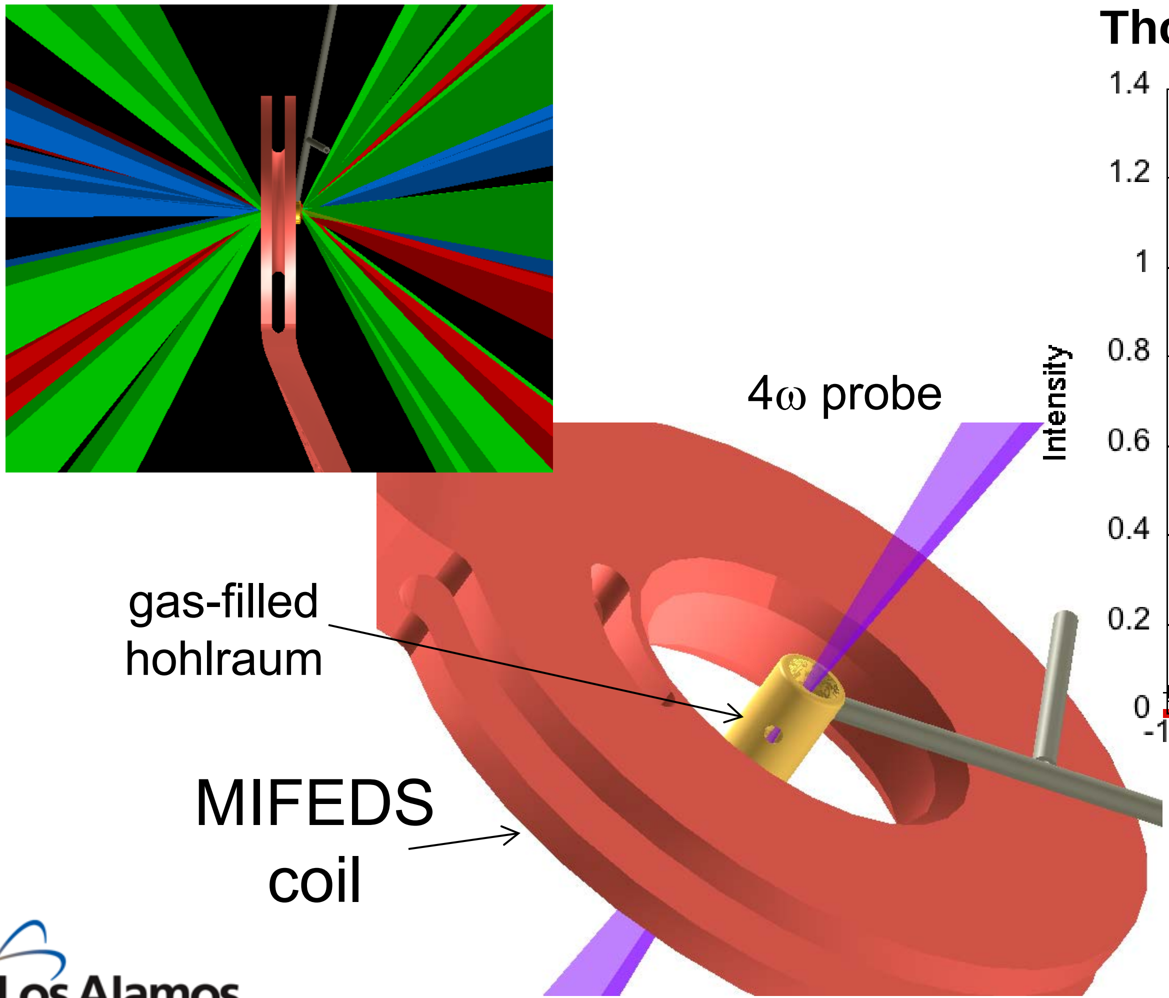
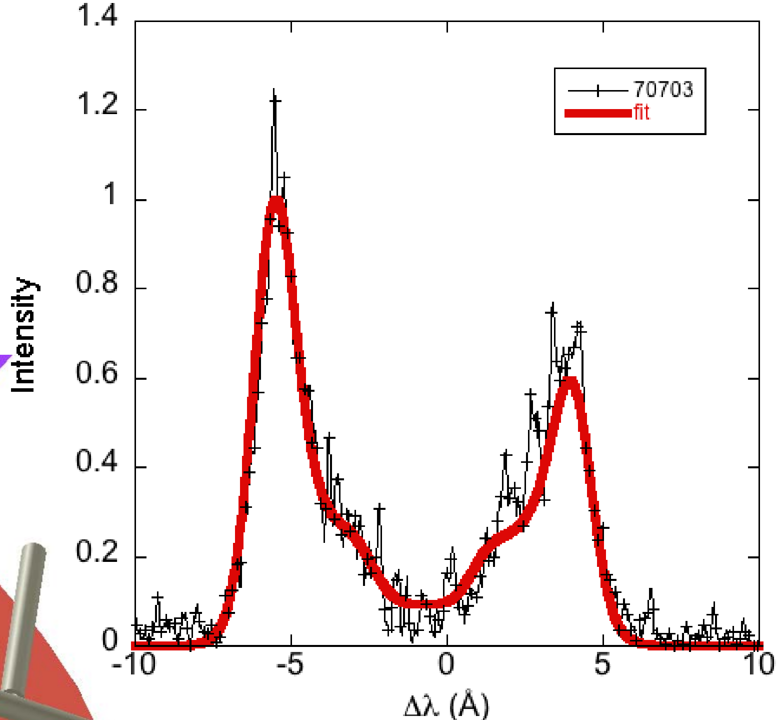
† Gotchev *et al., Rev. Sci. Instrum.* **80**, 043504 (2009).

Time-dependent plasma temperatures are measured using 4ω Thomson scattering



Thomson spectrum at t = 1-ns



multi-species form factor fit: $T_e \pm$ 0.1-keV

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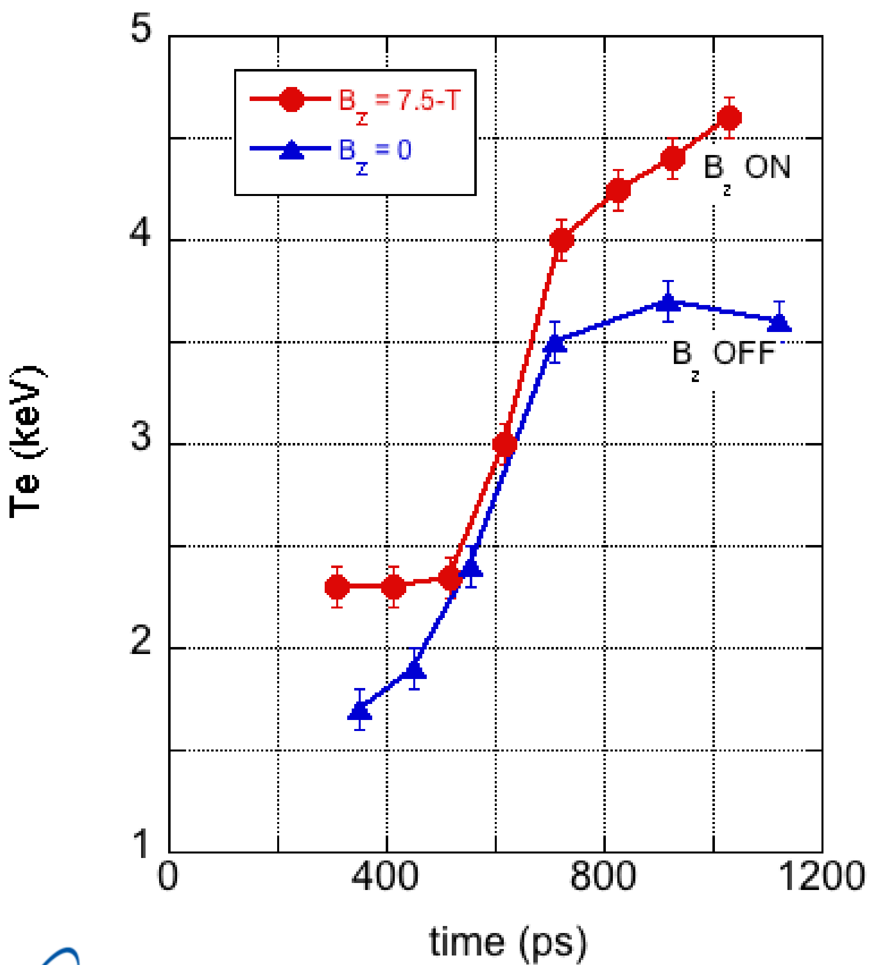
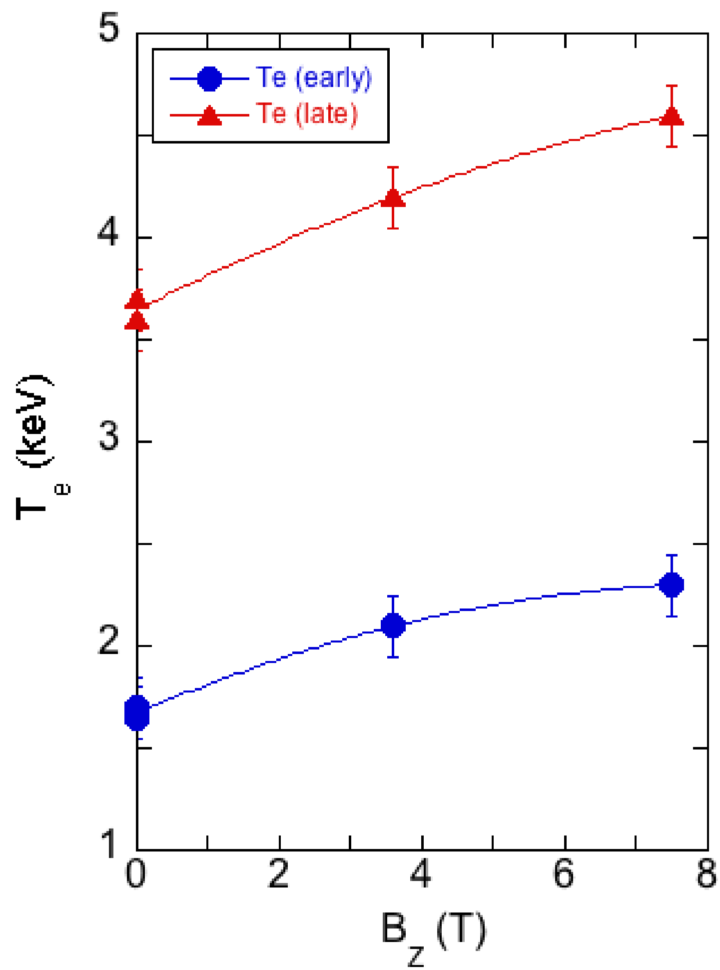
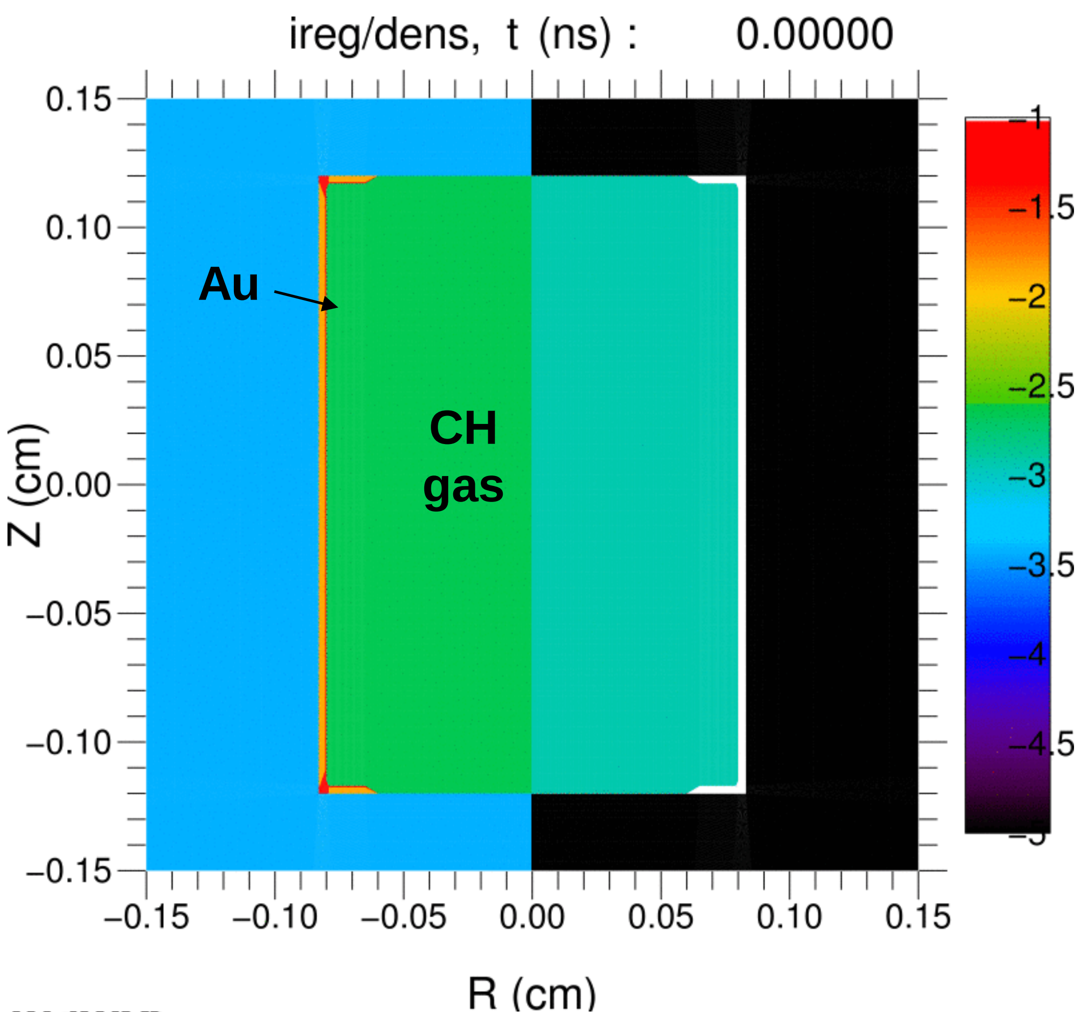
A substantial increase in plasma temperature is observed with external B-field





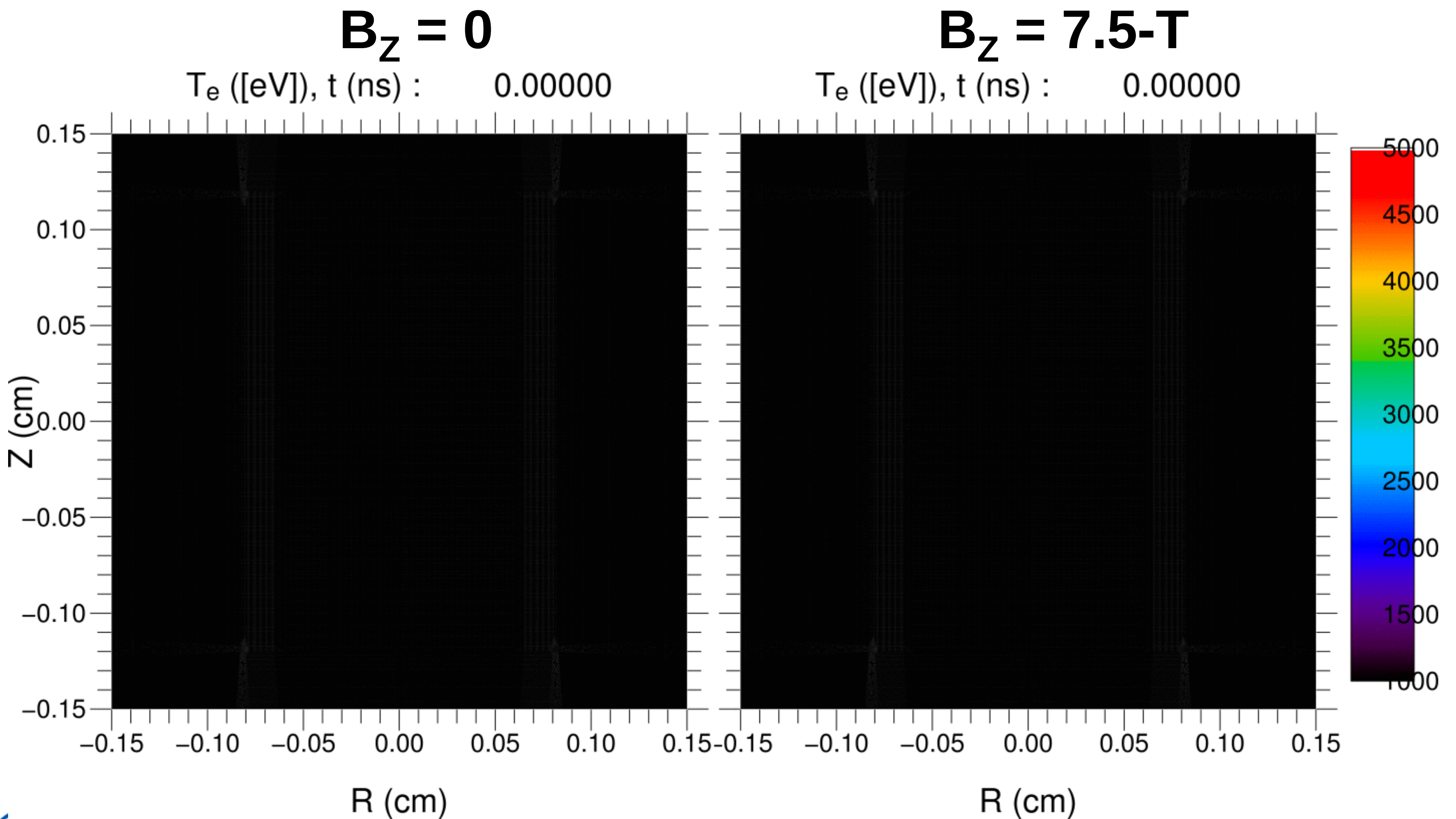
Material regions and log(density) contour plots from 2-D HYDRA simulations - movie



- **Material regions**
  Au (red)
  CH gas (green)
- **Log(density)**
- **Plots very similar with and without B_z**

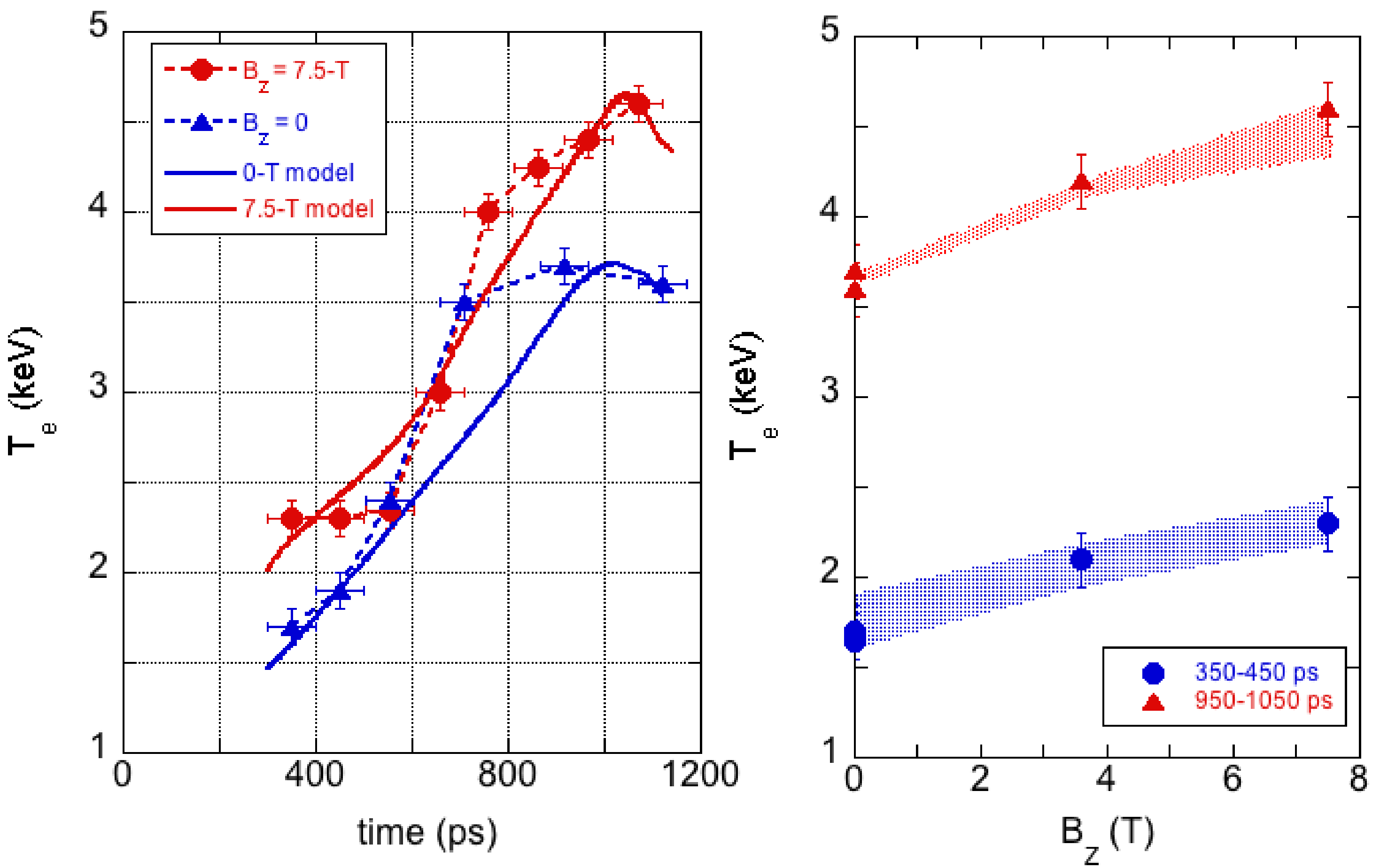
  (i.e. β >> 1, B-field affects thermal conduction but not hydro)

2-D HYDRA simulations show an increase in plasma temperature with external B_z = 7.5-T



movie

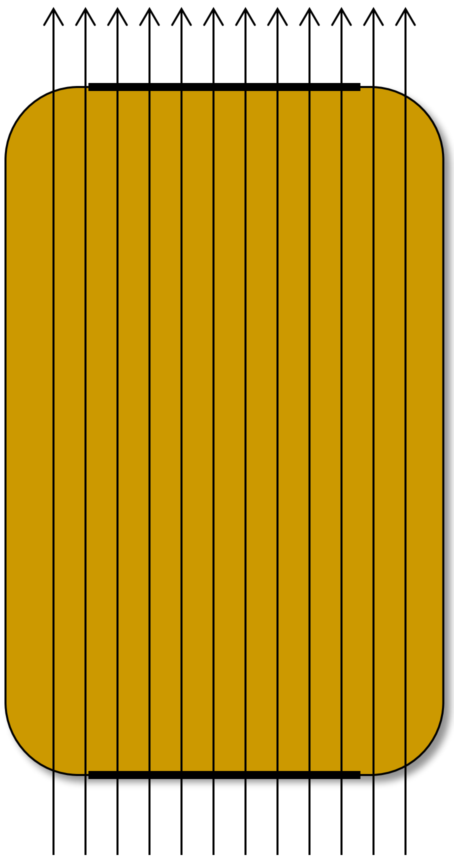
2-D HYDRA modeling is in good agreement with measured plasma temperatures†



- **HYDRA model:**
  - used measured laser parameters
  - flux limiter f = 0.05
  - no self-fields
  - overall trends compare well
  - rapid temperature rise not captured at intermediate times (sampling region different between expt & model).

† D.S. Montgomery *et al.*, *Phys. Plasmas* (2015)

What is the limit for an empty hohlraum with very large B_z?? (conduction only)



B_z

Assume straight field lines

B_z very large: $\kappa_\perp / \kappa_\| \approx 0$, but parallel losses remain

For unmagnetized:

$Q_\| \approx \frac{1}{4} Q_\perp$ since the ratio of areas $\left(A_\perp + A_\|\right)/A_\| \approx 4$

Unmagnetized heat flux: $Q \sim T_e^{7/2}$

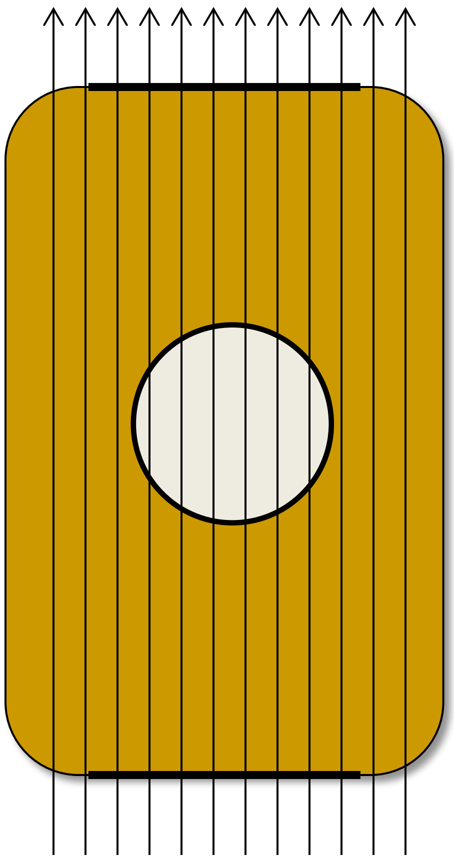
Maximum increase: $4^{2/7} \approx 1.48$

2-D HYDRA:

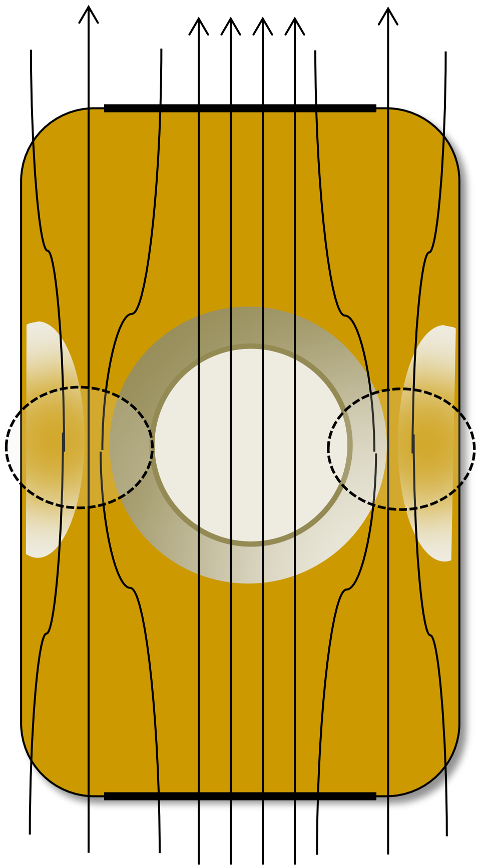
B_z = 0	T_{max} ~ 3.7 keV
B_z = 7.5-T	T_{max} ~ 4.65 keV
B_z = 60-T	T_{max} ~ 4.82 keV

What about a hohlraum with a capsule? (cartoon not a simulation)

t=0



B_z



B_z

t ~ several ns

Magnetic mirror?

T/T_0 much larger?

Will need 2-D HYDRA simulations …

Summary and Conclusions

- **Increased underdense plasma temperatures are desirable for NIF ignition hohlraums**
  - improve laser propagation through long-scale-length low-Z plasma (less inverse bremsstrahlung absorption)
  - possibly mitigate LPI with higher T_e (higher $k\lambda_D$, more Landau damping)
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- **Omega experiments using gas-filled hohlraums demonstrate an increased plasma temperature with B_z = 7.5-T**
  - plasma conditions measured with 4ω Thomson scattering
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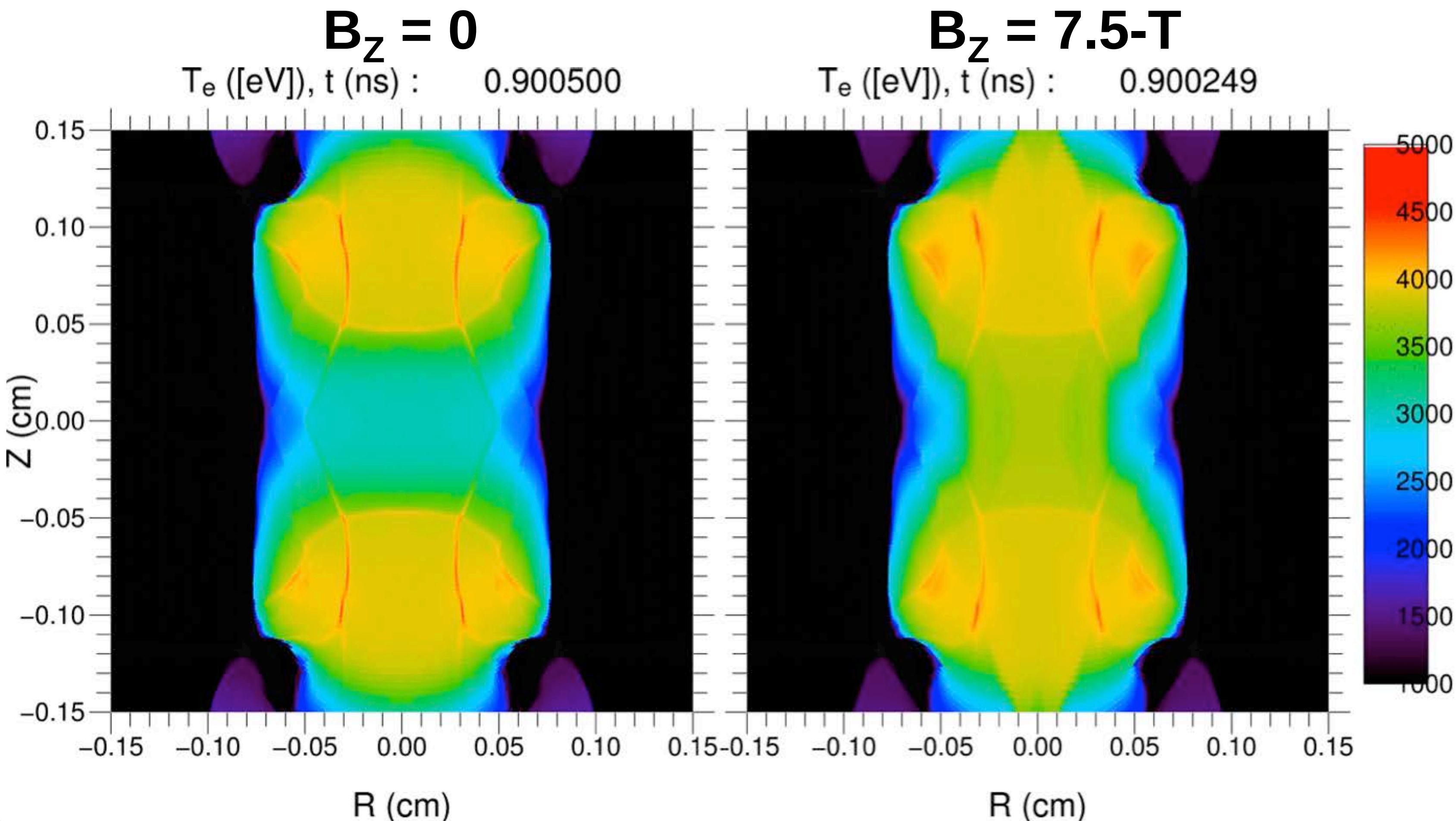
BACKUPS

2-D HYDRA simulations show an increase in plasma temperature with external B_z = 7.5-T



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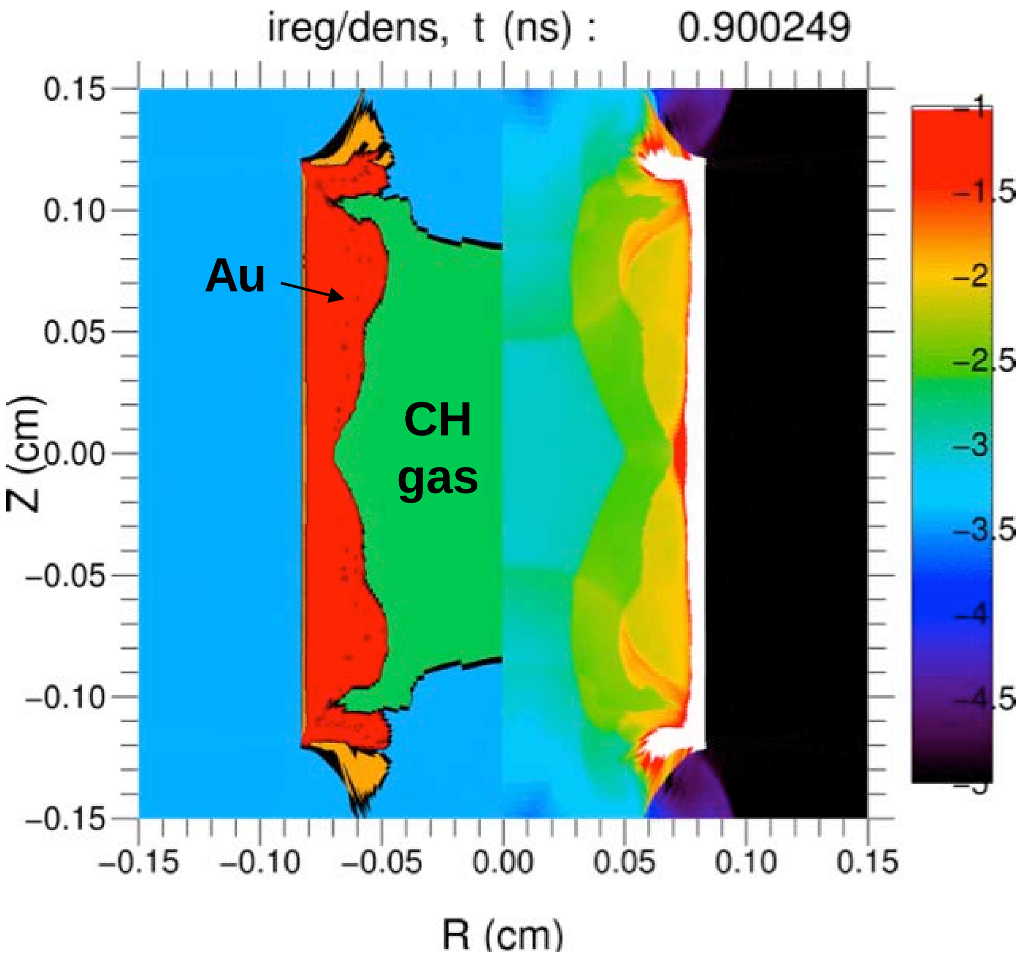
Material regions and log(density) contour plots from 2-D HYDRA simulations at t=0.9-ns



- **Material regions**
  Au (red)
  CH gas (green)
- **Log(density)**
- **Plots very similar with and without B_z**

  (i.e. $\beta >> 1$, B-field affects thermal conduction but not hydro)

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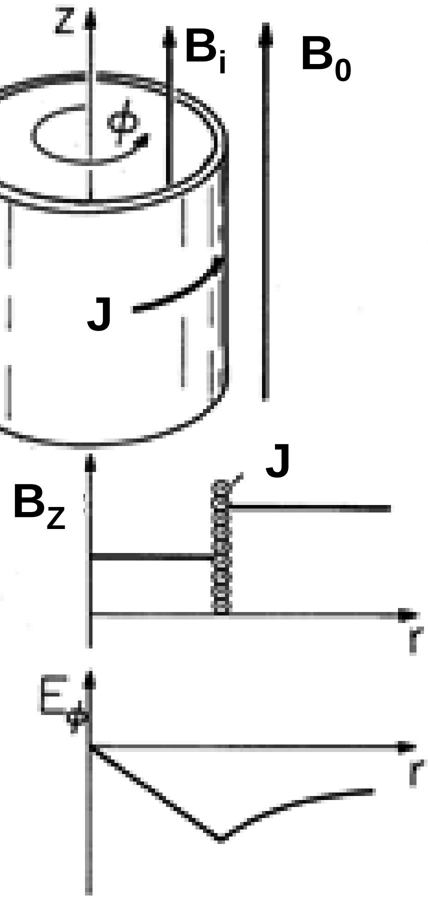
Finite diffusion time for magnetic field into the Au cylindrical hohlraum due to eddy currents



$$\frac{dB_i}{dt} + \frac{B_i}{\tau_m} = \frac{B_0}{\tau_m}$$

B_z turned on instantly at t=0

$$\tau_m = \frac{1}{2}\mu_0 \sigma \Delta a$$

Thin conducting shell of radius *a*, thickness Δ, conductivity σ

$$B_i = B_0\left(1 - e^{-t/\tau_m}\right)$$

Omega Hohlraum	NIF Hohlraum
a = 0.8 mm	a = 2.5 mm
Δ = 5-μm	Δ = 25-μm
σ_{Au} = 4e7 (ohm-m)$^{-1}$	σ_{Au} = 4e7 (ohm-m)$^{-1}$
τ_m ~ 100-ns	τ_m ~ 1.6-μs

σ_{Au} is for 99.9% pure Au at room temperature, consider adding impurities, e.g. 0.5% at. Ti + 99.5% Au decreases σ to 1e7 (ohm-m)$^{-1}$, then τ_m ~ 400-ns.

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Ignition Hohlraum Simulations with Imposed Magnetic Field, and Effect on Hot Electrons

NIF Magnetic Field Workshop

12 October 2015

David J. Strozzi, J. M. Koning, L. J. Perkins,
M. M. Marinak, D. J. Larson, B. G. Logan

LLNL-PRES-???
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

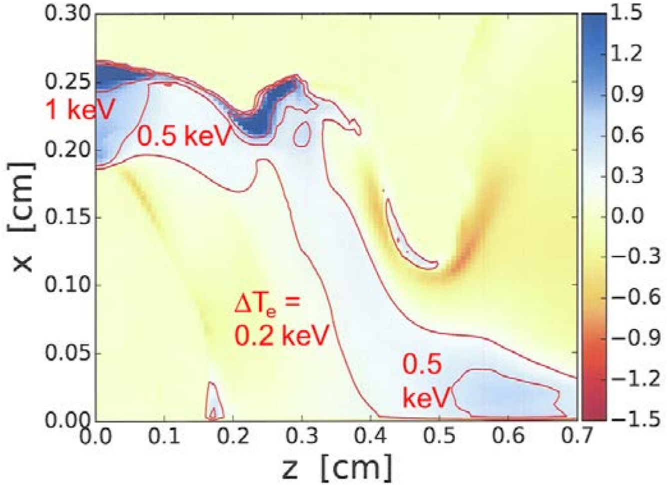
Lawrence Livermore National Laboratory

Summary: axial B field impacts hohlraum rad-hydro and hot electrons

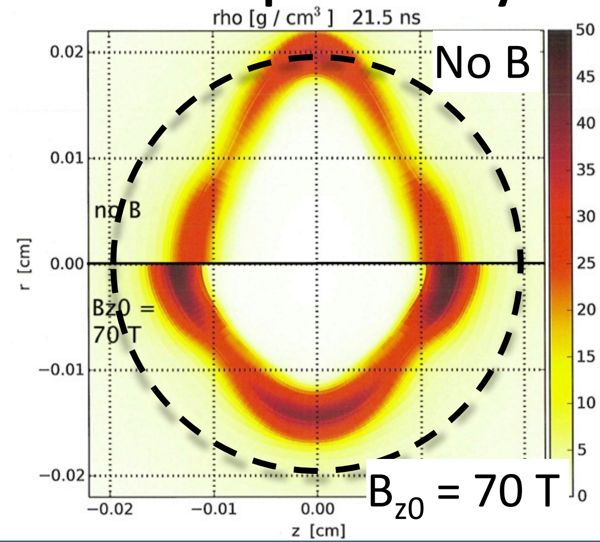
- Axial field of 70 Tesla: goal for NIF

Raises temperature, esp. near wall

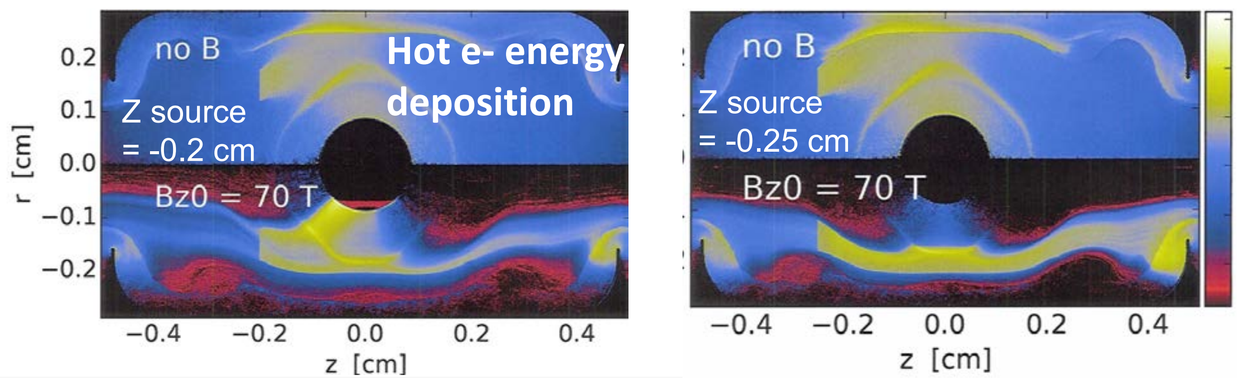
e- temperature: with B - without B [keV]



Improves inner beam propagation: Increased equator x-ray drive



Hot electrons magnetized in fill gas: guided to or away from capsule



D. J. Strozzi et al., Journ. Plasma Physics (submitted), arxiv.org/abs/1508.00803

Hydra MHD model: simple Ohm's law, reduced heat conduction across B the main effect

Single-fluid, quasi-neutral, "Ohmic": no e- inertia or displacement current

Faraday: $\partial_t \vec{B} = -\nabla \times \vec{E}$

Ampère: $\mu_0 \vec{J} = \nabla \times \vec{B}$

Blue: how MHD / B field affect matter

Mass continuity: $\partial_t \rho_m + \nabla \cdot \left(\rho_m \vec{V} \right) = 0$

JxB force / magnetic pressure

CM velocity: $\rho_m \left(\partial_t + \vec{V} \cdot \nabla \right) \vec{V} = \rho \vec{E} + \vec{J} \times \vec{B} - \nabla p$

0: quasi-neutral

Ohm's law: inertia-less e- momentum equation:

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{\vec{J}}{n_e e} \times \vec{B} - \frac{\nabla p_e}{n_e e} + \overleftrightarrow{\eta} \cdot \vec{J} - e^{-1} \overleftrightarrow{\beta} \cdot \nabla T_e$$

Full Braginskii 1965

$$= -\vec{v} \times \vec{B} + \eta \cdot \vec{J}$$

Used in this work

Electron energy equation:

Reduced conduction perp. to B

Ohmic heating

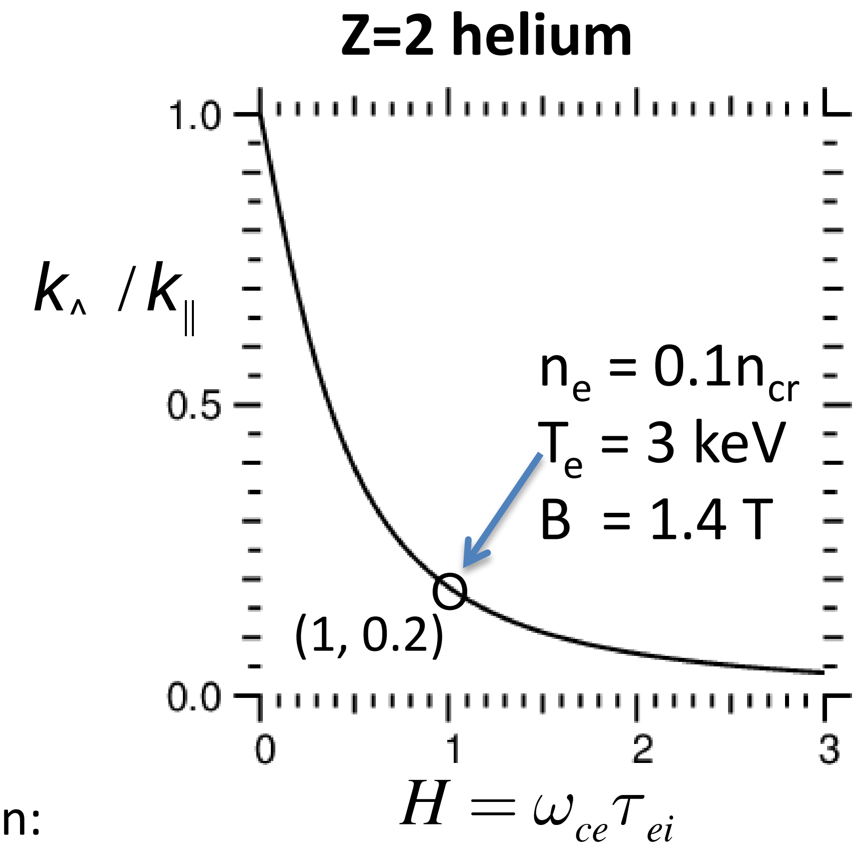
$$\rho \frac{d\varepsilon}{dT_e} \partial_t T_e + p_e \nabla \cdot \vec{v} = \xi_{ei} (T_i - T_e) - \nabla \cdot \left[\left(\left(\kappa_\parallel - \kappa_\perp \right) \hat{\mathbf{b}} \hat{\mathbf{b}} + \kappa_\perp \overleftrightarrow{\mathbf{I}} \right) \nabla T_e \right] + \eta J^2 + \ldots$$

e- heat conduction perpendicular to B strongly suppressed in underdense low-Z fill for B > 1 T

$$\frac{\kappa_\perp}{\kappa_\parallel} \approx \frac{1+p_1H}{1+p_2H+p_3H^2+p_4H^3}$$

$H \equiv \omega_{ce}\tau_{ei}$ Hall parameter

p_i depend on Z_i

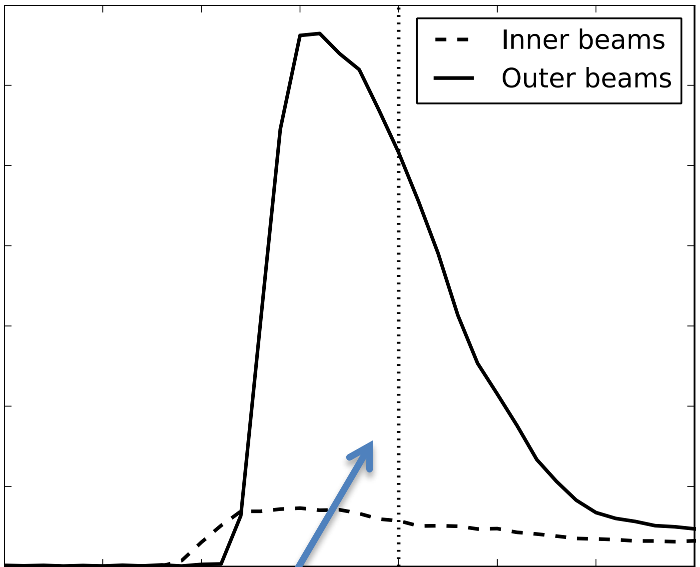


Reduced perpendicular heat conduction:

- Increases electron temperature
- Improves inner beam propagation

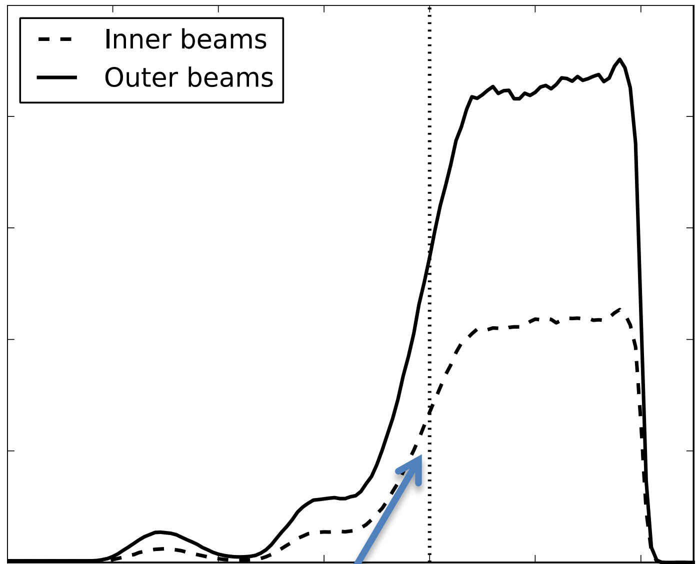
NIF shot N120321: low-foot pulse, CH ablator, DT ice layer

Picket



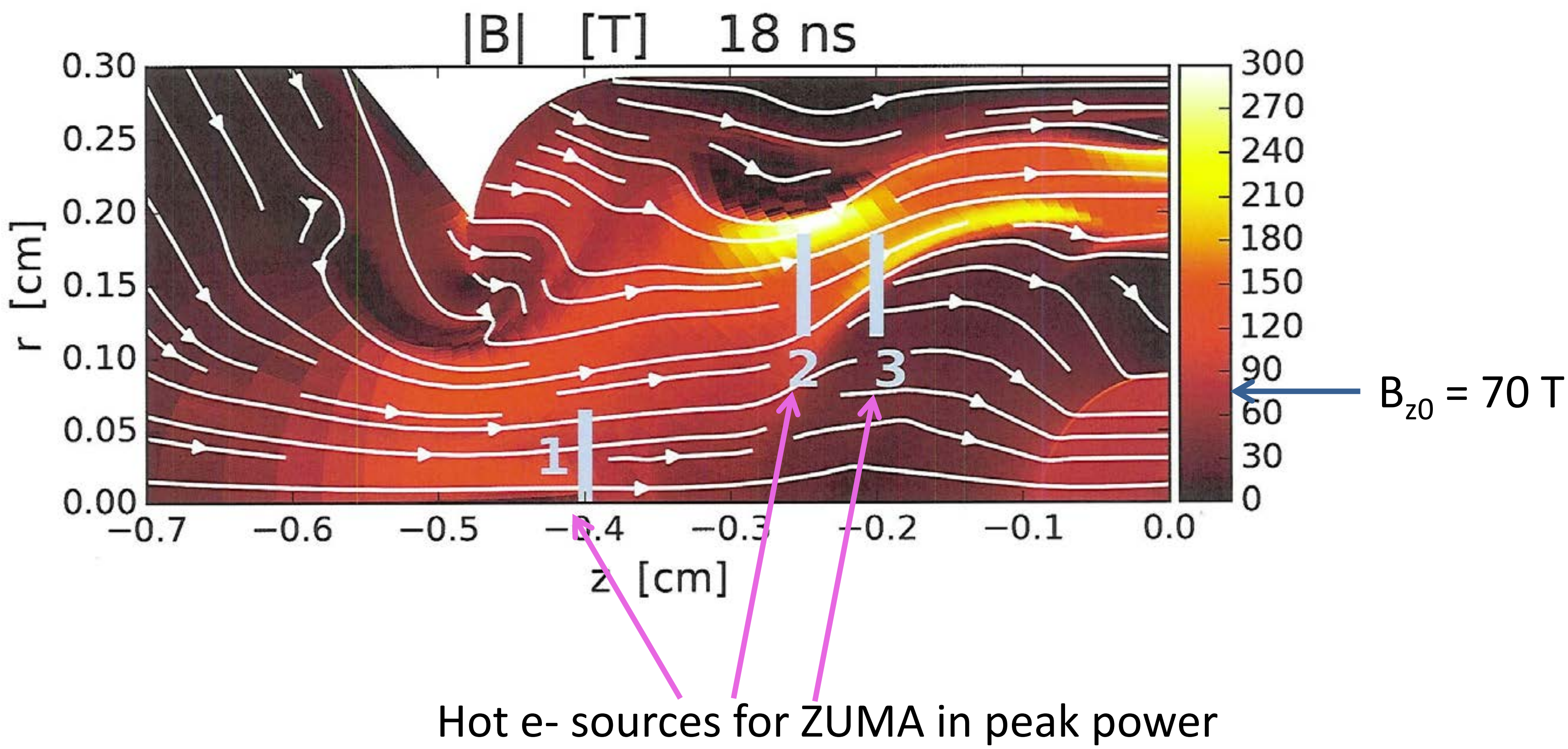
Time used for two-plasmon hot e- Zuma study

Peak power



Time used for direct-on-capsule and SRS hot e- Zuma studies

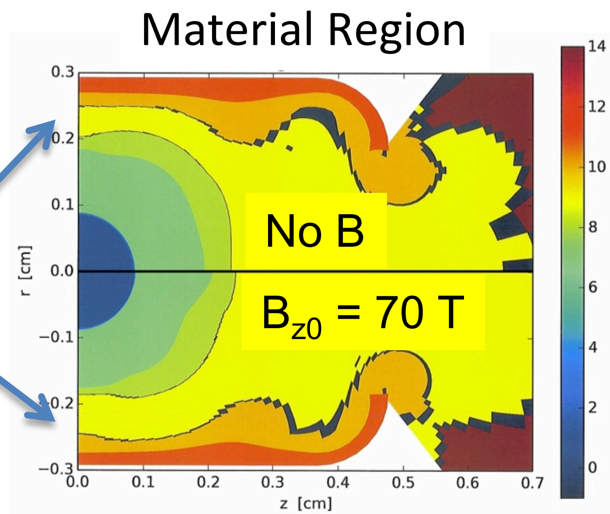
Magnetic field early in peak power advected by plasma flow: "frozen-in law" holds



Increased T_e: hotter fill and wall, less material in inner beam path near wall with 70 T axial field

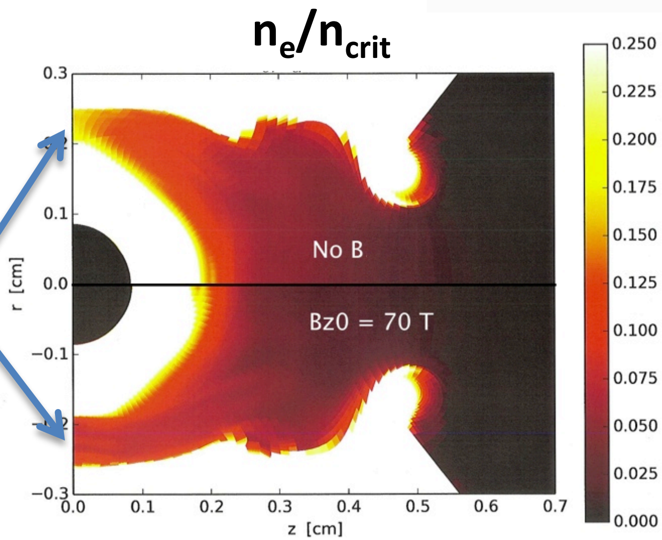
NIT shot N120321
18 ns: early peak power

Wider equator channel with B

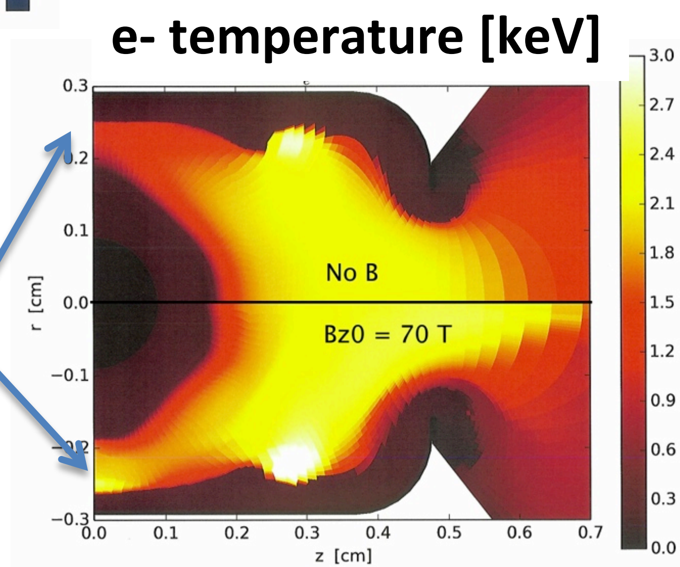


Each figure is a hohlraum quadrant with (top) and without (bottom) B field

Less n_e w/ B



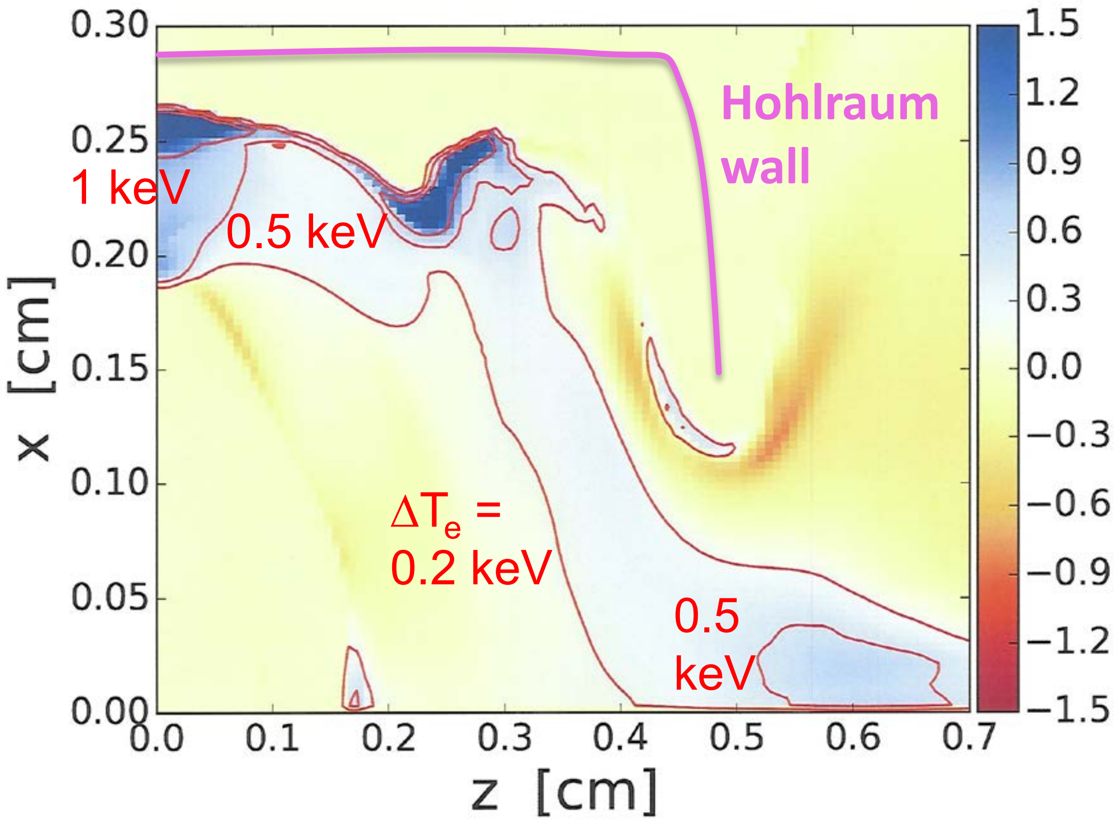
Higher T_e w/ B, esp. on equator



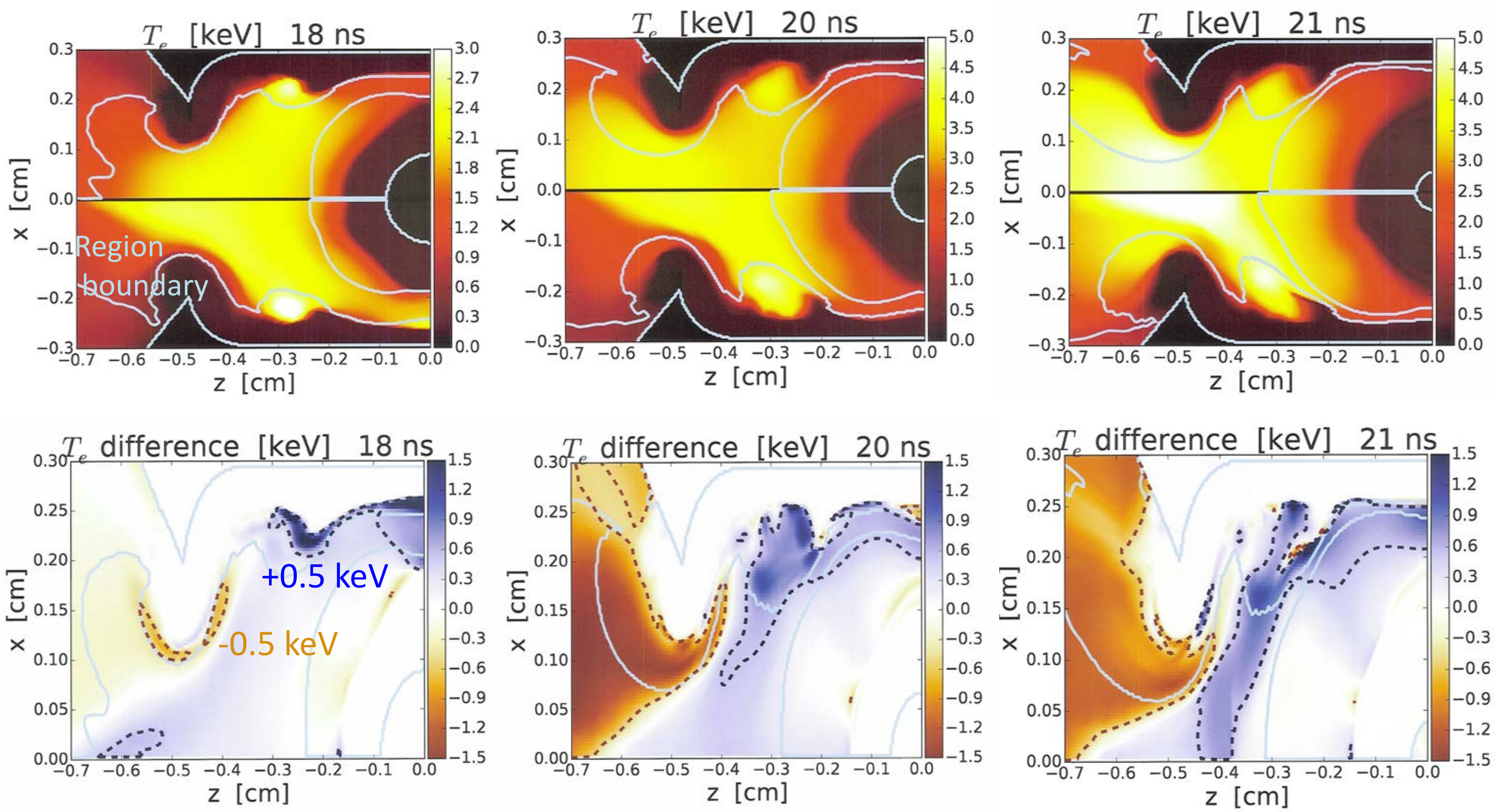
Increased T_e: with B field, T_e is 0.5 – 1.5 keV hotter near wall, < 0.5 keV in rest of fill

18 ns: start of peak power

E- temperature difference at 18 ns: With B – without B [keV]



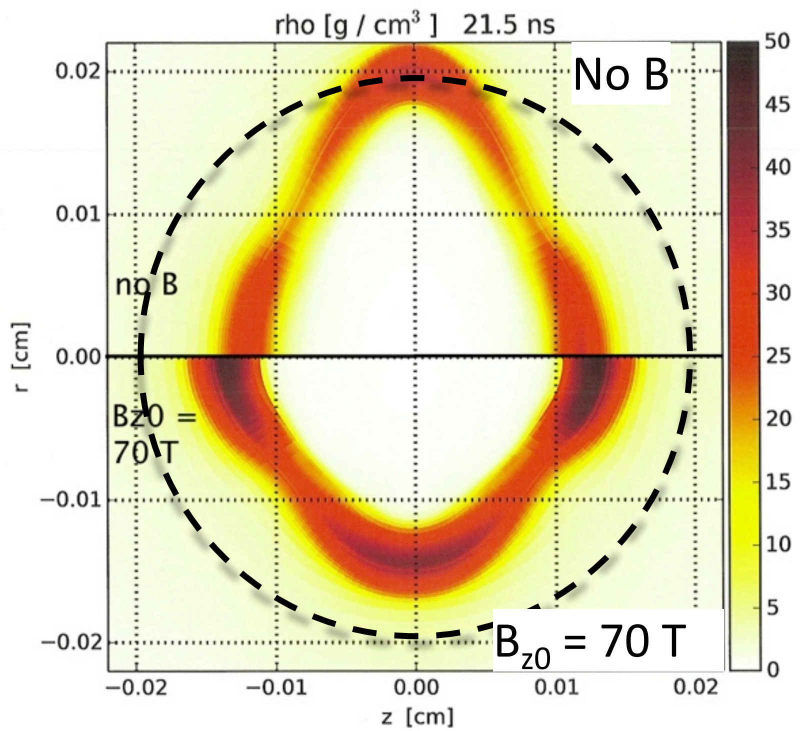
T_e at various times: largest increase with field in gold

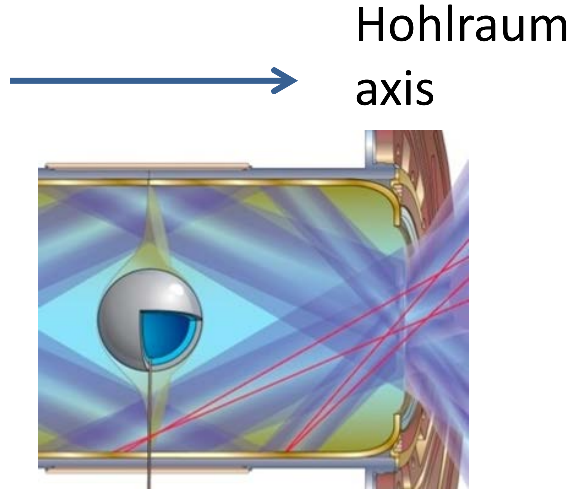


Inner beam propagation: B field reduces inner beam absorption in fill, less pancaked implosion

NIF Shot N120321: 21.5 ns: end of pulse

- Shell radius ~ 150 um
- No B: shell oblate (pancaked)
- With B: close to round, better inner-beam propagation





Hot electrons: ZUMA[1] (D. J. Larson): Hybrid PIC code: kinetic hots, dense plasma background

Run here in “Monte-Carlo” mode:

- Hot electrons undergo collisional drag and angular scatter[2]
- Lorentz force from time-independent B field; no E field

Drag (energy loss):
~ 1/[e- energy]

$$\frac{dE}{ds} = -\frac{C_e n_e}{m_e v^2} L_d$$

$$\approx \frac{C_e n_e}{2E} \ln\left[\frac{E}{\hbar\omega_{pe}}\right] \qquad \hbar\omega_{pe} \ll E \ll m_e c^2$$

$$L_d = \ln\left[\frac{\beta\varepsilon^{1/2}}{2^{1/2}}\frac{m_e c^2}{\hbar\omega_{pe}}\right] + \frac{9}{16} + \frac{1/8 + \ln 2}{\gamma} * \left(-1 + \frac{1}{2\gamma}\right)$$

$$C_e \equiv \frac{e^4}{4\pi\varepsilon_0{}^2}$$

Angular scatter:
~ 1/[e- energy]$^{3/2}$

$$\frac{d\left\langle\theta^2\right\rangle}{ds} = \frac{2C_e}{p^2 v^2}\left[L_{sI}\sum_i n_i Z_i{}^2 + n_e L_{se}\right]$$

$$\approx \frac{C_e n_e}{2E^2}\left(\frac{\left\langle Z^2\right\rangle}{\left\langle Z\right\rangle} + 1\right) \ln \frac{2(2T_e E)^{1/2}}{\hbar\omega_{pe}} \qquad E \ll m_e c^2$$

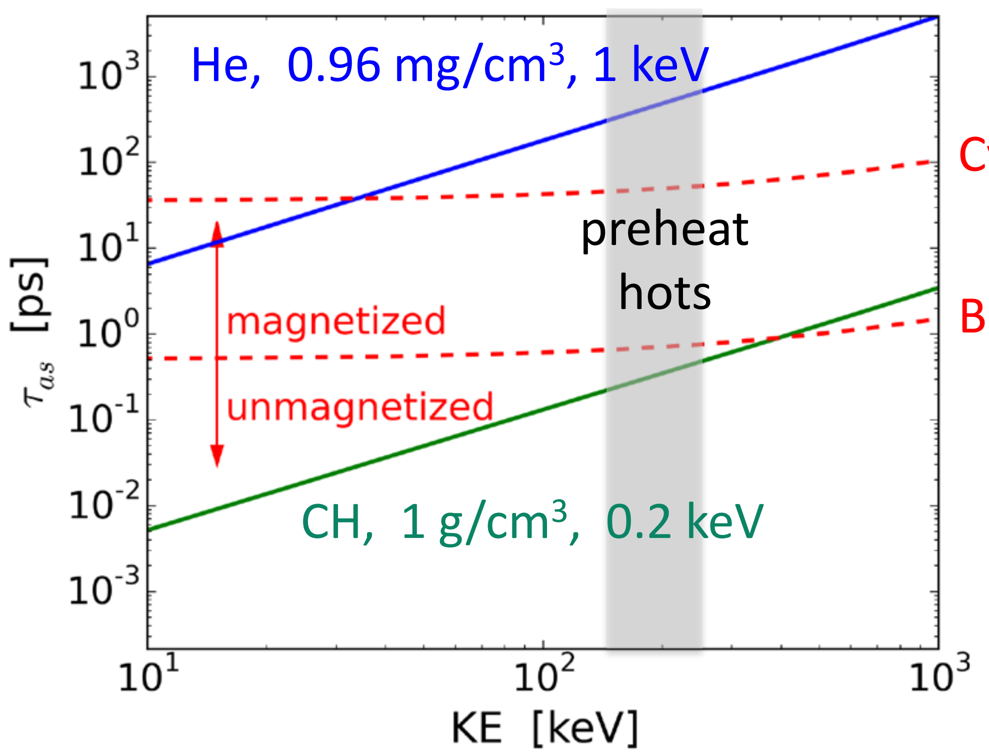
$$L_{sI} = \ln\frac{2\lambda_{De} p}{\hbar} - 0.234 - 0.659\beta^2 \qquad L_{se} = L_{sI} - \frac{1}{2}\ln\frac{\gamma+3}{2}$$

[1] D. J. Larson et al., APS-DPP 2010; D. J. Strozzi et al., Phys. Plasmas 2012

[2] A. P. L. Robinson et al., Nuclear Fusion 2014

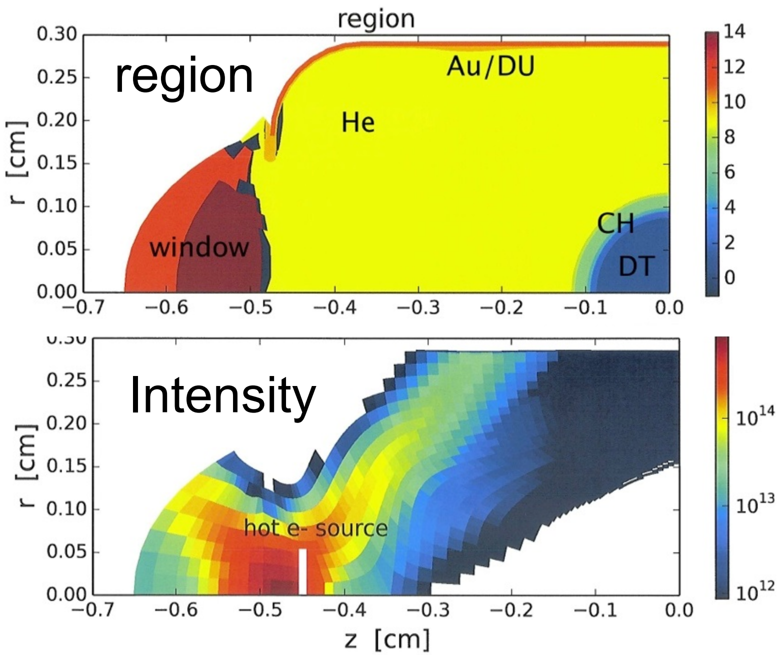
Adding 1 Tesla field strongly magnetizes hots in underdense fill, weakly in dense ablator

Time for r.m.s. 90 deg. angular scatter

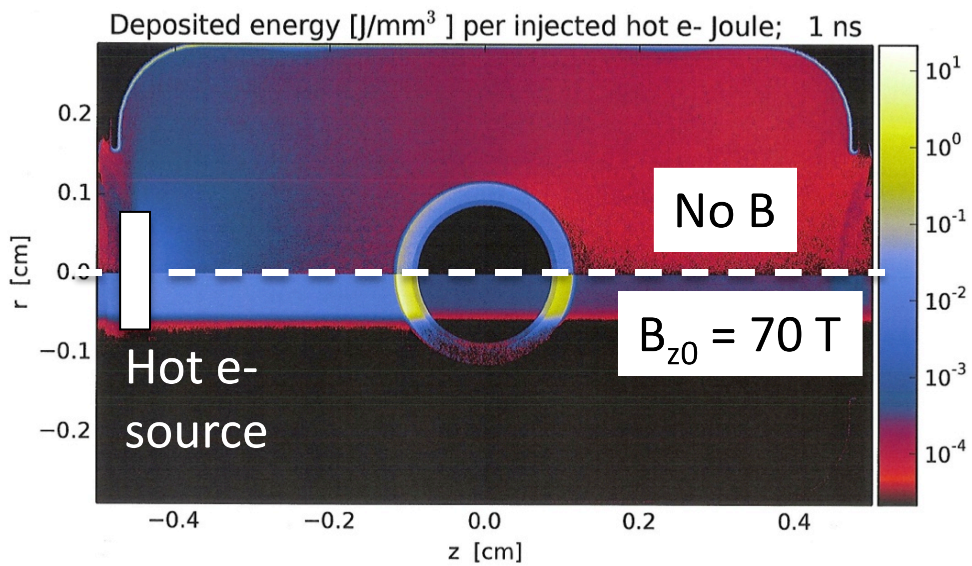


Hot electrons: Picket with two-plasmon hot e- source in window: B field guides hots to capsule

NIF shot N120321 @ 1 ns



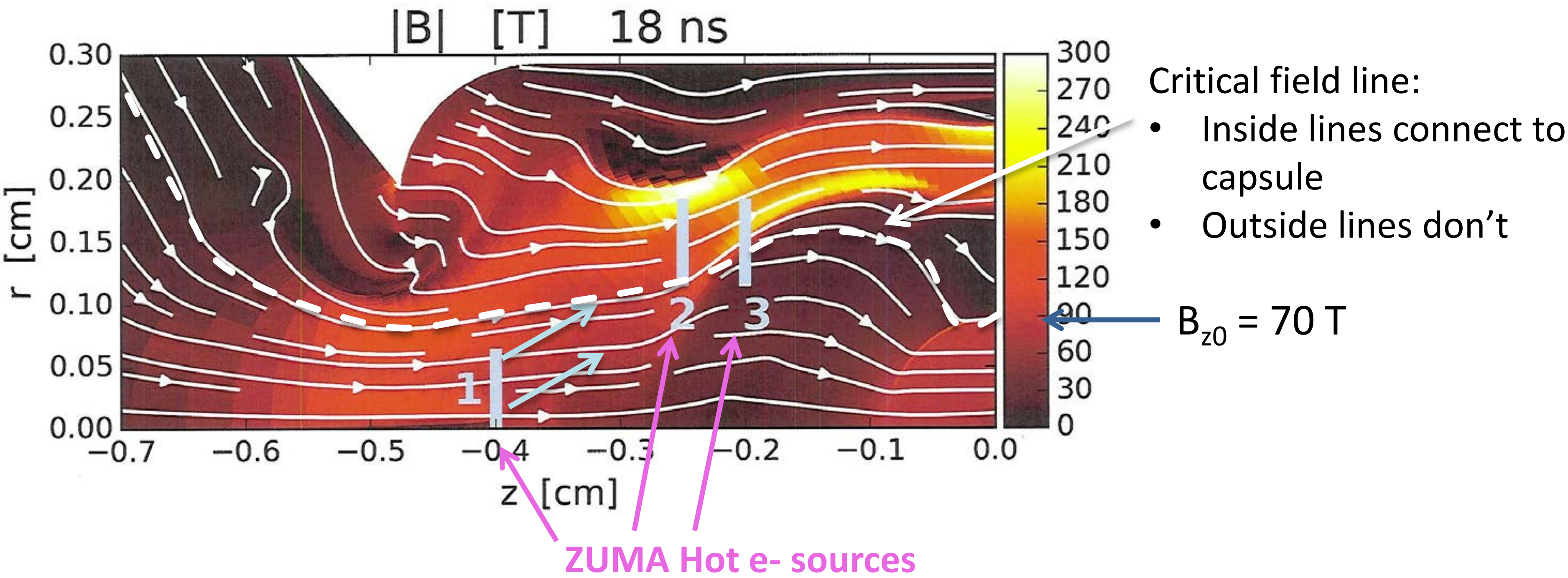
Hot electron energy deposited



- Two-plasmon decay hot e- source: T_{hot} = 80 keV, R=500 um, $dN/d\Omega$ = const. for $v_z > 0$
- B_z = 70 T (uniform): hot e-'s magnetized in fill, transported directly at capsule
- Fraction of hot e- energy deposited in DT ice: no B: $2.2*10^{-3}$, with B: 0.026 (12x higher)
    - Still only ~20 mJ so OK?
- Pre-heat concentrated along poles – may be shape issue
- Preheat depends on hot e- production, tunable by picket pulse shape (e.g. low-power "toe")

B field lines roughly follow MHD frozen-in law: advected with conducting plasma

N120321, 18 ns: early peak power



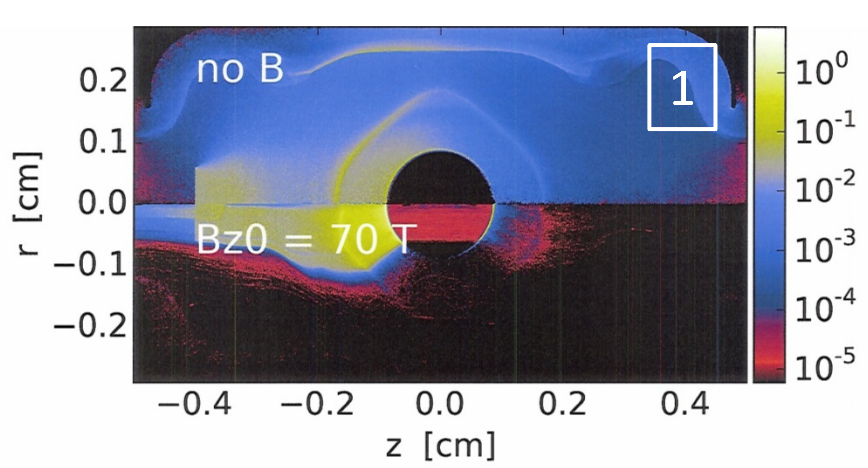
- Field increases where compressed between ablator and wall
- Some field lines connect to capsule, some don't

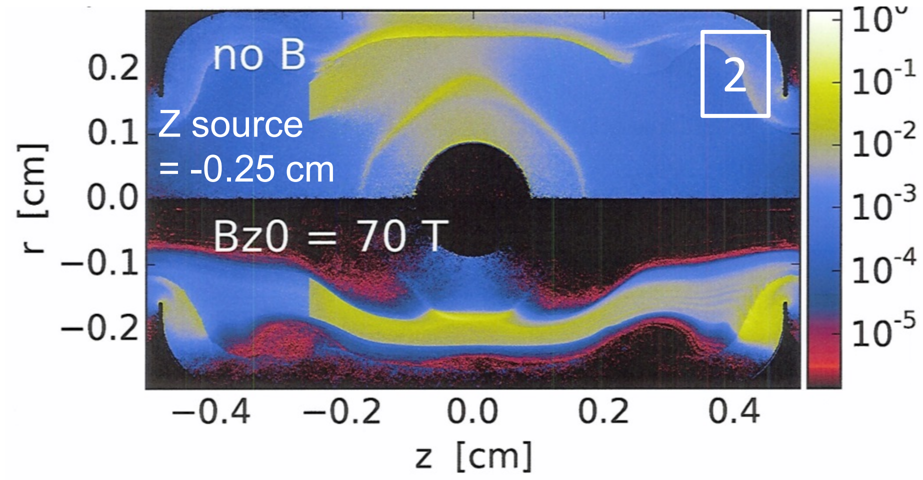
SRS source:

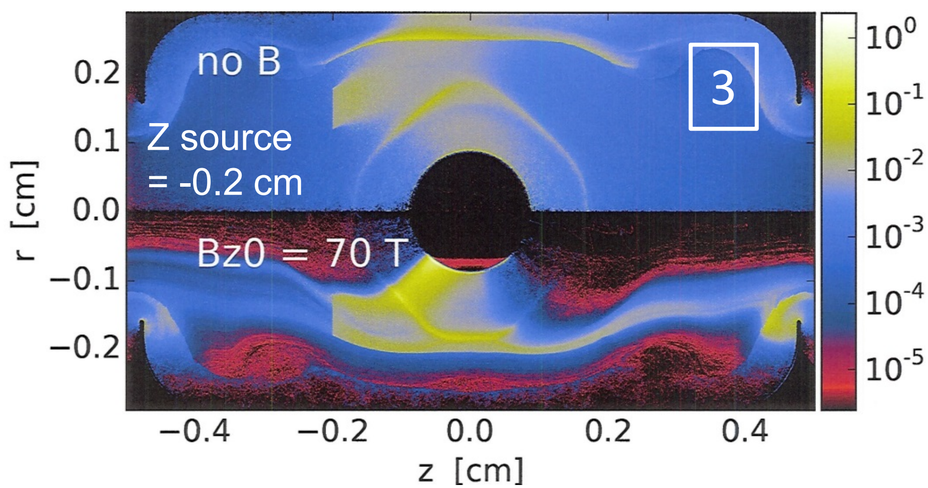
- T_{hot} = 30 keV
- Angle spectrum: $dN/d\Omega = \exp[-((\theta-27^o)/10^o)^4]$

Hot electrons: coupling to DT early in peak power is very sensitive to source location

Coupled energy [J/mm^3] per injected hot e- Joule







Fraction of hot e- energy coupled to DT ice

Source	No B	B_{z0} = 70 T	B_{z0} / no B
1	3.58E-4	2.89E-3	8.07
2	1.37E-4	3.44E-6	0.025
3	1.19E-4	1.26E-3	10.6

Conclusion: imposed B field may improve inner beam propagation, could help or hurt hot electron preheat

Hydra MHD simulation of low-foot shot N120321, with 70 T initial axial field:

- Cross-field electron heat conduction greatly reduced
- Leads to hotter and less dense equator, better inner-beam propagation
- May reduce inner-beam SRS

Zuma studies of hot electron propagation:

- Picket: two-plasmon source in window guided to capsule, energy coupled to DT 12x higher
- Peak power: SRS source confined to He fill, energy coupled to DT strongly depends on source location
- Story may change if hot electrons made no field lines still connected to capsule

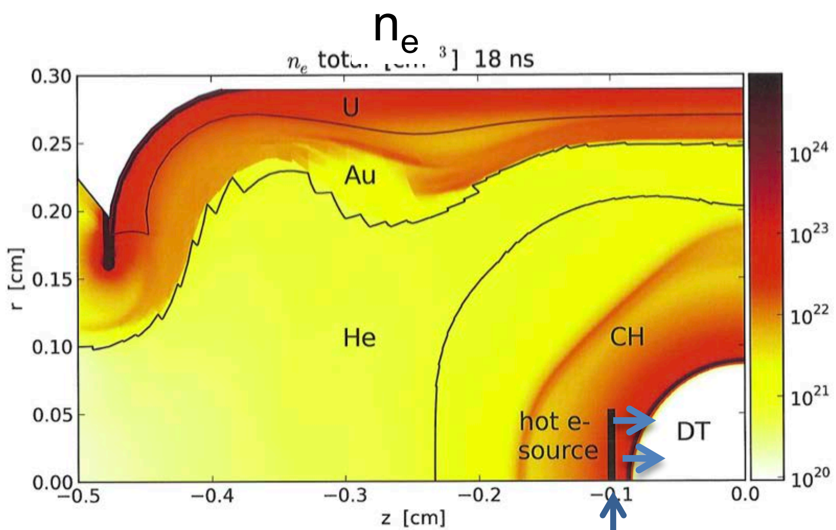
Future work:

- “Biermann” self-generated fields: numerics being investigated
- Nernst effect may significantly affect imposed-field dynamics (A. Joglekar, PRL 2014 and Anomalous Absorption 2015)

BACKUP BELOW HERE

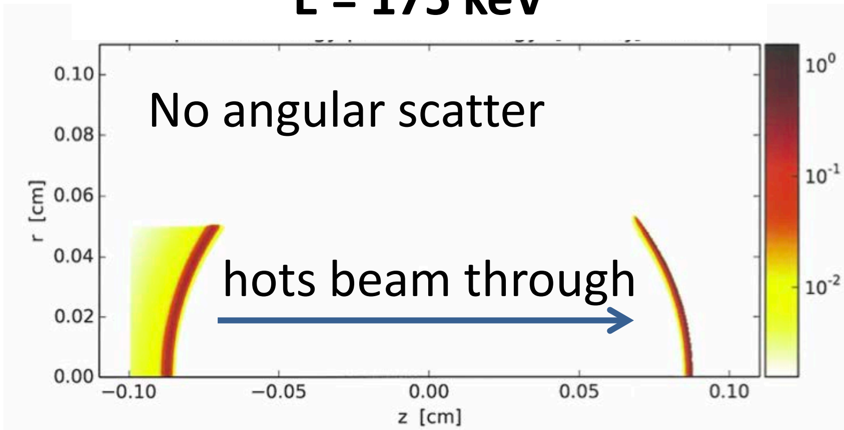
Hot electron test case: source directly incident on capsule

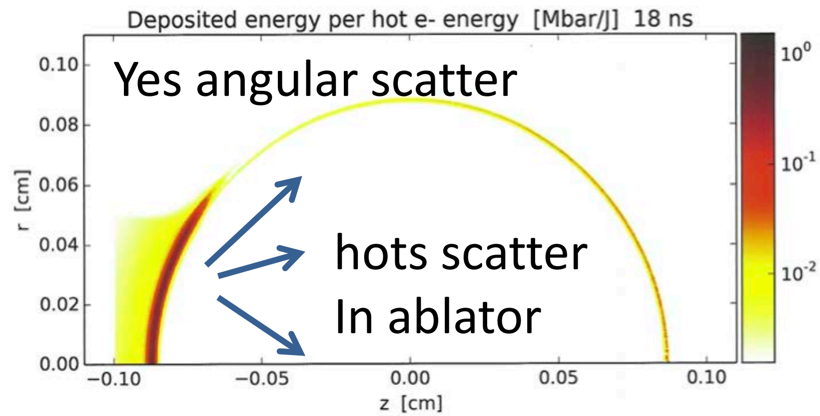
N120321   18 ns: early peak power



Unphysical test source:
Mono-energetic, collimated

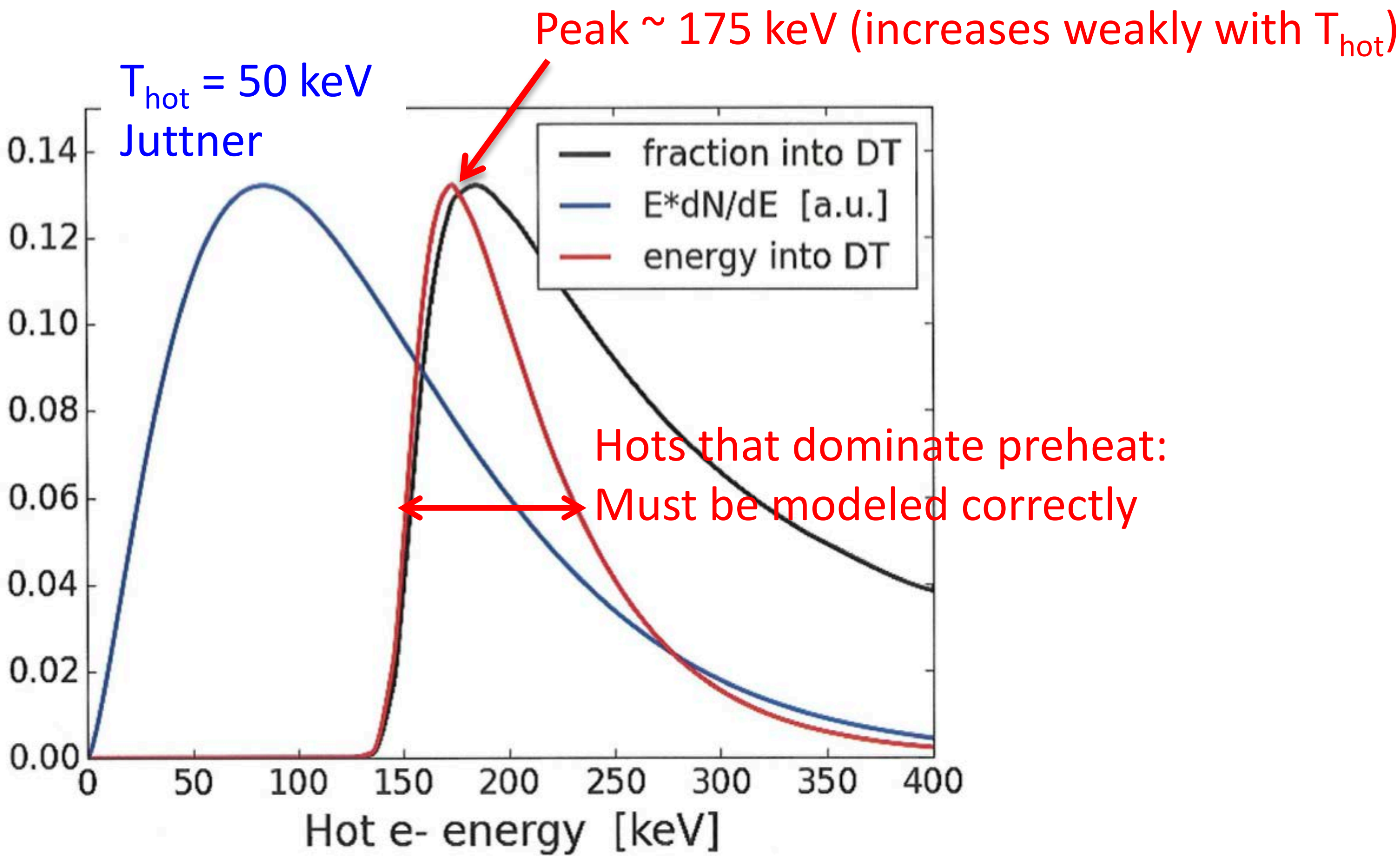
Energy deposited per volume
E = 175 keV



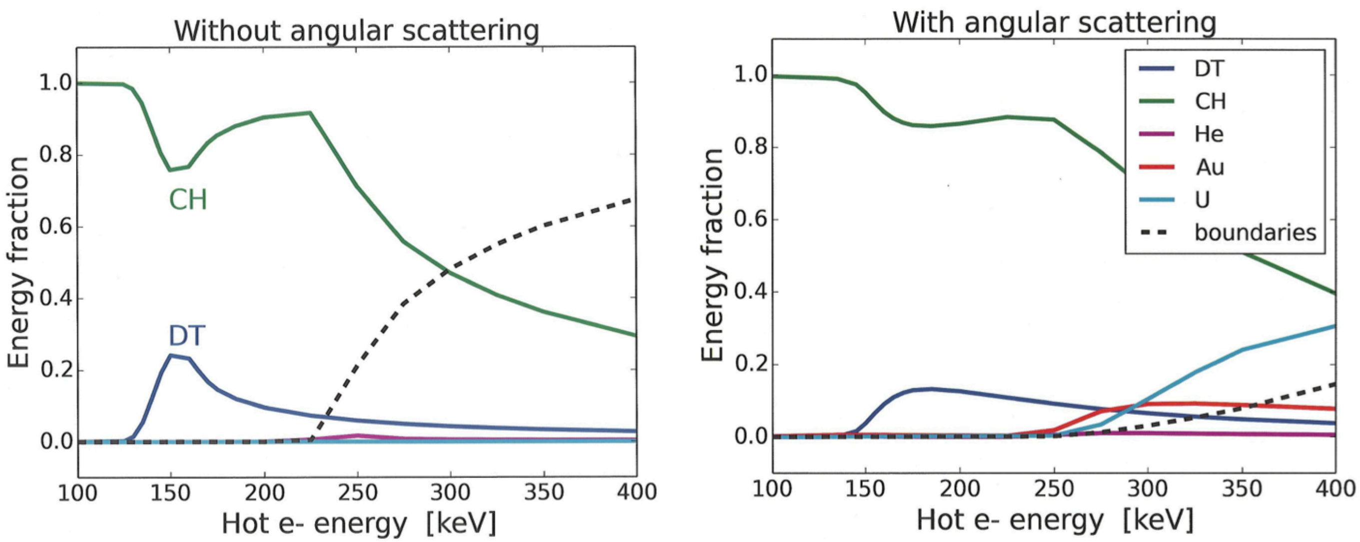


Hot electron test case: preheat given by 150 to 250 keV electrons

"Gamow peak": Energy to DT = coupling efficiency * hot e- energy spectrum

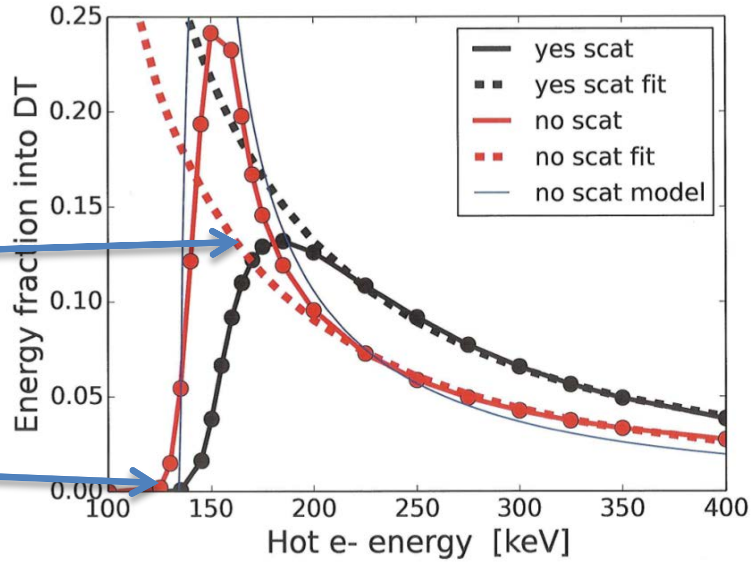


Hot electron test case: E > 130 keV to reach DT, 185 keV couple best



185 keV couple best to DT

130 keV to reach DT



2 page Physics summary (1)

Experiment: Enhancing multi-keV x-ray sources with B-fields

Experiment: XRSD_Kshell_Bfield?
Responsible Org: LLNL
NIF shots from: XRSD/NSA?
Shot RI: May/Moore?
Engineer: Rhodes?
Designer: Kemp/Colvin

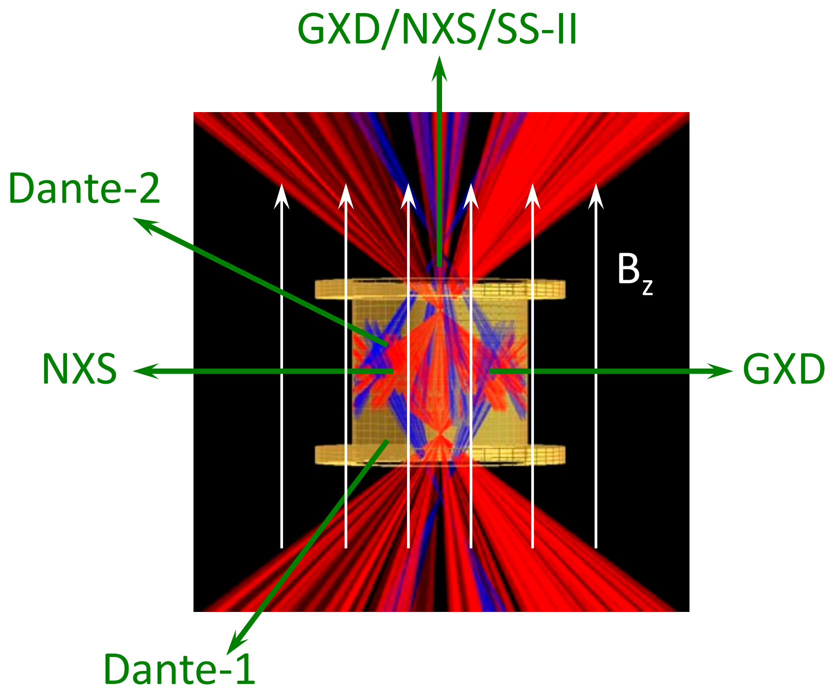
Experimental objectives: Increase plasma temperatures in low density, high-Z gas and foam targets to enhance multi-keV K-shell radiation used for x-ray sources

Key physics related to having a B-field: Inhibited electron thermal transport with imposed magnetic fields

Expected results: Enhanced K-shell emission, hotter x-ray spectra from Dante, NXS, SS-II and GXD

Important aspects of the experiment:

- **Key B-field requirements: *10-50 T*, *25%* uniformity, *>10 μs* rise time**
- **Potentially more than <u>double</u> K-shell emission in Kr/Ag/Xe targets**
- **Enhancement can be tested with phased increases in *B***

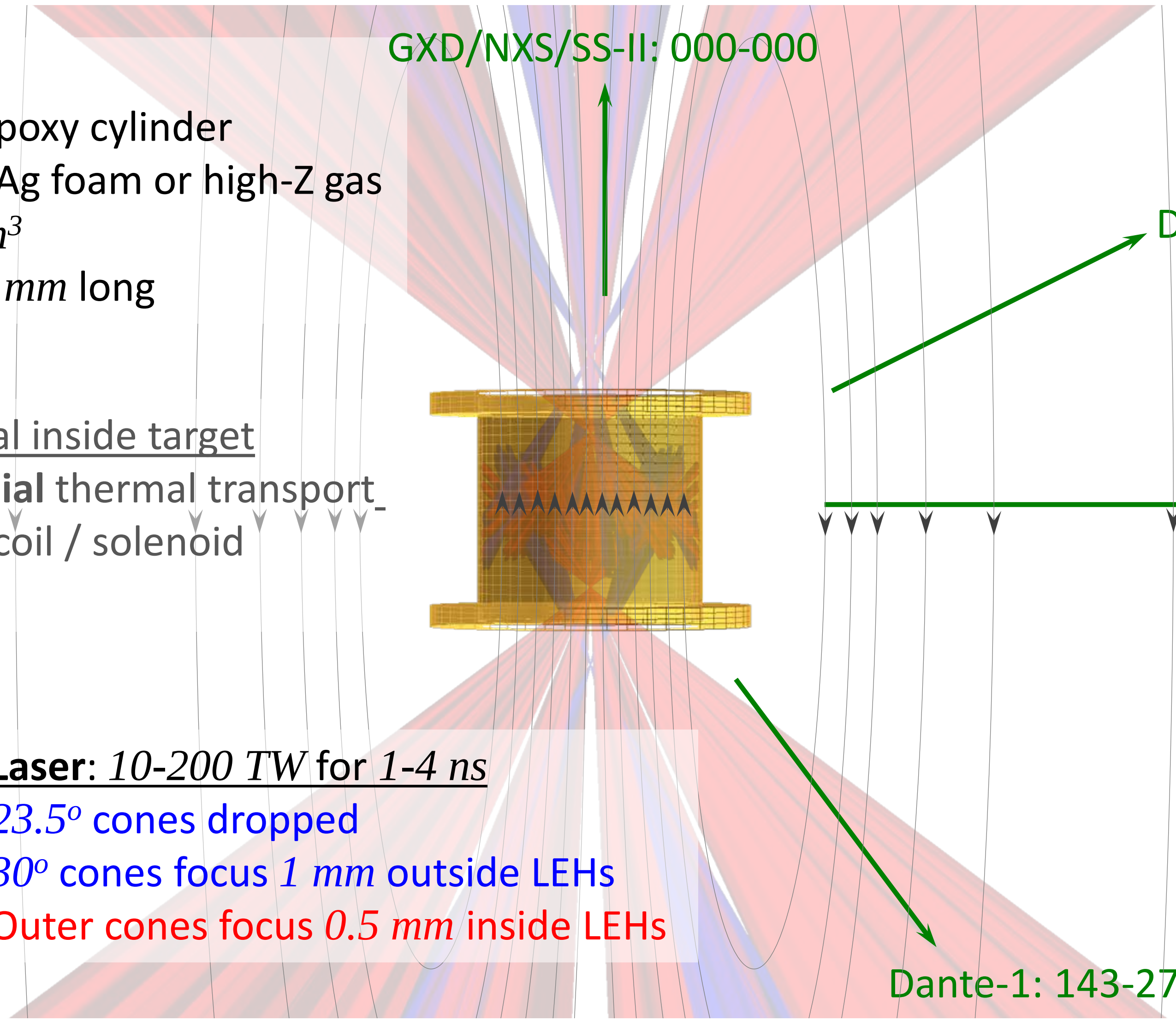


2 page Physics summary (2)

Experiment: Enhancing multi-keV x-ray sources with B-fields

Target:
Thin-wall epoxy cylinder
Filled with Ag foam or high-Z gas
5-20 mg/cm³ → $5\text{-}20\ mg/cm^3$
$4\ mm\ \phi \times 4\ mm$ long

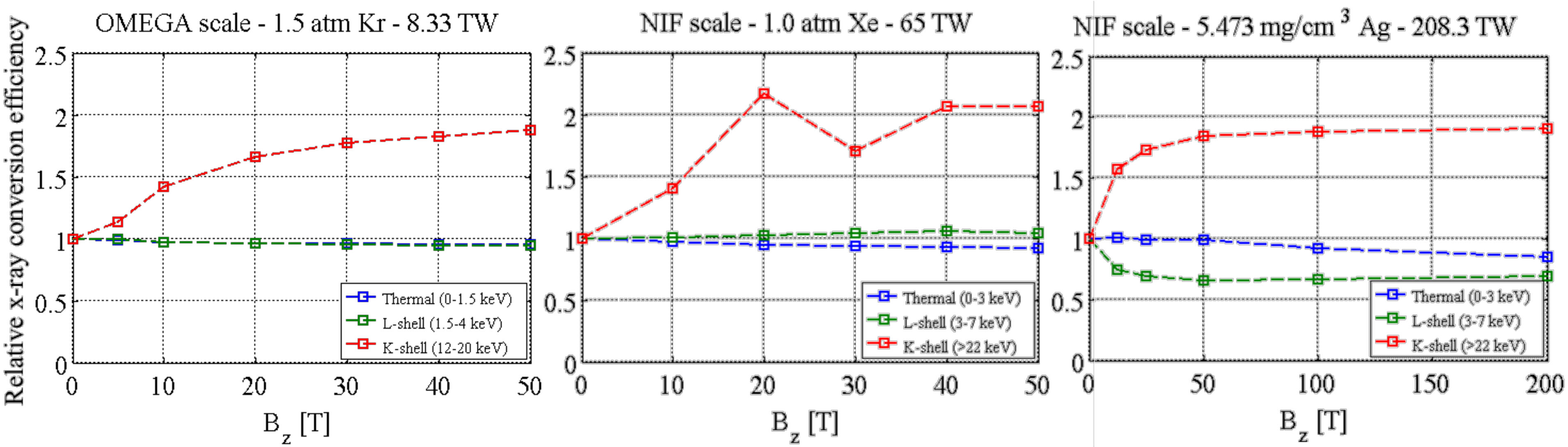
B-field: axial inside target
Inhibits **radial** thermal transport
Helmholtz coil / solenoid
$B_z \leq 50\ T$



Laser: *10-200 TW* for *1-4 ns*
23.5^o cones dropped
30^o cones focus *1 mm* outside LEHs
Outer cones focus *0.5 mm* inside LEHs

This experiment requires a $B_z \leq 50\ T$ and uniformity to 25%

HYDRA simulation results with resistive MHD package and constant external B_z



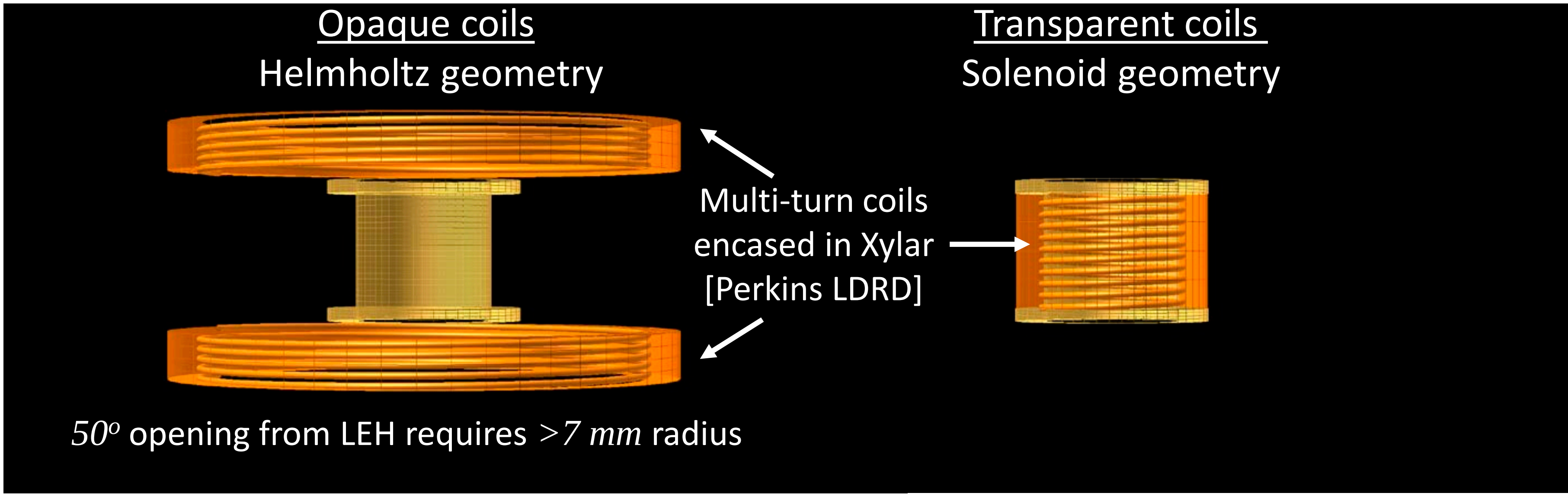
50 T external B_z could <u>double</u> laser-driven *10-30 keV* K-shell emission *for otherwise underpowered interactions*

Beneficial for either <u>*>20 keV* sources</u> which use all of NIF (SGEMP or materials effects testing) or <u>~*10 keV* backlighters</u> which only use a fraction of NIF

Uniformity requirements most stringent for lower field strengths: *±10%* in X-ray yield (Dante uncertainty) corresponds to better than *25%* uniformity @ *10 T*, *50% @ 50 T*

This experiment requires a magnetized volume of $0.25\ cm^3$

Material samples are typically located along 90º line-of-sight: coils cannot block emission



Helmholtz geometry		Solenoid geometry
Vetted MIFEDS style approach	⟷	Untested, but akin to J. Perkins LDRD design
More target	⟷	Less target debris
debris	⟷	Smaller radius/current
Larger radius/current	⟷	More uniform fields
Less uniform fields	⟷	Integrated
Independent	⟷	No line-of-sight issues
Line-of-sight issues	⟷	Additional attenuation of ≤ L-shell emission
Unmodified ≤L-shell emission	⟷	No unconverted light concerns
Requires unconverted light-shields		

Requirement: **B-field rise-time**

This experiment requires the field to turn on no faster than *10 μs* for a *50 T* B_z-field

Assumptions:

- Spatially uniform B_z rises linearly from zero to peak field strength (*50 T*) in time τ
- Cylindrical (semi-infinite) Ag foam of radius $R = 0.2\ cm$ and density $\rho = 5.473\ mg/cm^3$
- Volumetric expansion coefficient (α_o), specific heat capacity ($c_{p,o}$) independent of density
- Electrical $\sigma = (\rho/\rho_o)\ \sigma_o$ & thermal $k = (\rho/\rho_o)\ k_o$ conductivity linearly proportional to density
- Nonpermeable ($\mu = \mu_o$), negligible material motion and $dR = 40\ \mu m$ thick epoxy wall (insulator)

B-field turn on time considerations:

Field Ionization

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\oint_C \vec{E}\cdot d\vec{l} = -\frac{1}{c}\iint \frac{\partial \vec{B}}{\partial t}\cdot d\vec{A}$$

$$E_\phi = -\frac{r}{2c}\frac{\partial B_z}{\partial t}$$

$$E_{OTB} = \frac{U_{ion}^2}{4Ze^3}$$

$$\tau_{OTB} \approx \frac{4Ze^3}{2c}\frac{R\Delta B_z}{U_{ion}^2} = \boxed{2.9\,ps}$$

B-field Diffusion

$$\frac{\partial \vec{B}}{\partial t} = \frac{c^2}{4\pi\sigma}\nabla^2 \vec{B}$$

$$\nabla^2 B = \frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial B_z}{\partial r}\right] = \frac{1}{r}\frac{\partial B_z}{\partial r} + \frac{\partial^2 B_z}{\partial r^2}$$

$$\tau_{diff}^{Ag} \approx 0.173\frac{4\pi}{c^2}\sigma R^2 = \boxed{28.4\,ns}$$

$$\tau_{diff}^{wall} \approx \frac{1}{2}\left(\frac{R+dR}{R} - 1\right)\frac{4\pi}{c^2}\sigma R^2 << \tau_{diff}^{Ag}$$

Melting

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + \vec{j}\cdot\vec{E}$$

$$k\nabla^2 T = \frac{k}{r}\frac{\partial}{\partial r}\left[r\frac{\partial T}{\partial r}\right]$$

$$\vec{j}\cdot\vec{E} = \sigma\left(\frac{r}{2c}\frac{\partial B_z}{\partial t}\right)^2$$

If we ignore thermal losses…

$$\frac{\partial T}{\partial t} = \frac{\sigma}{\rho c_p}\left(\frac{r}{2c}\frac{\partial B_z}{\partial t}\right)^2$$

$$\tau_{melt}^{k=0} \approx \frac{\sigma}{\rho c_p}\left(\frac{r\Delta B_z}{2c}\right)^2\frac{1}{\Delta T} = \boxed{68\,\mu s}$$

MHD w/ HYDRA:

1D cylindrical geometry

LEOS

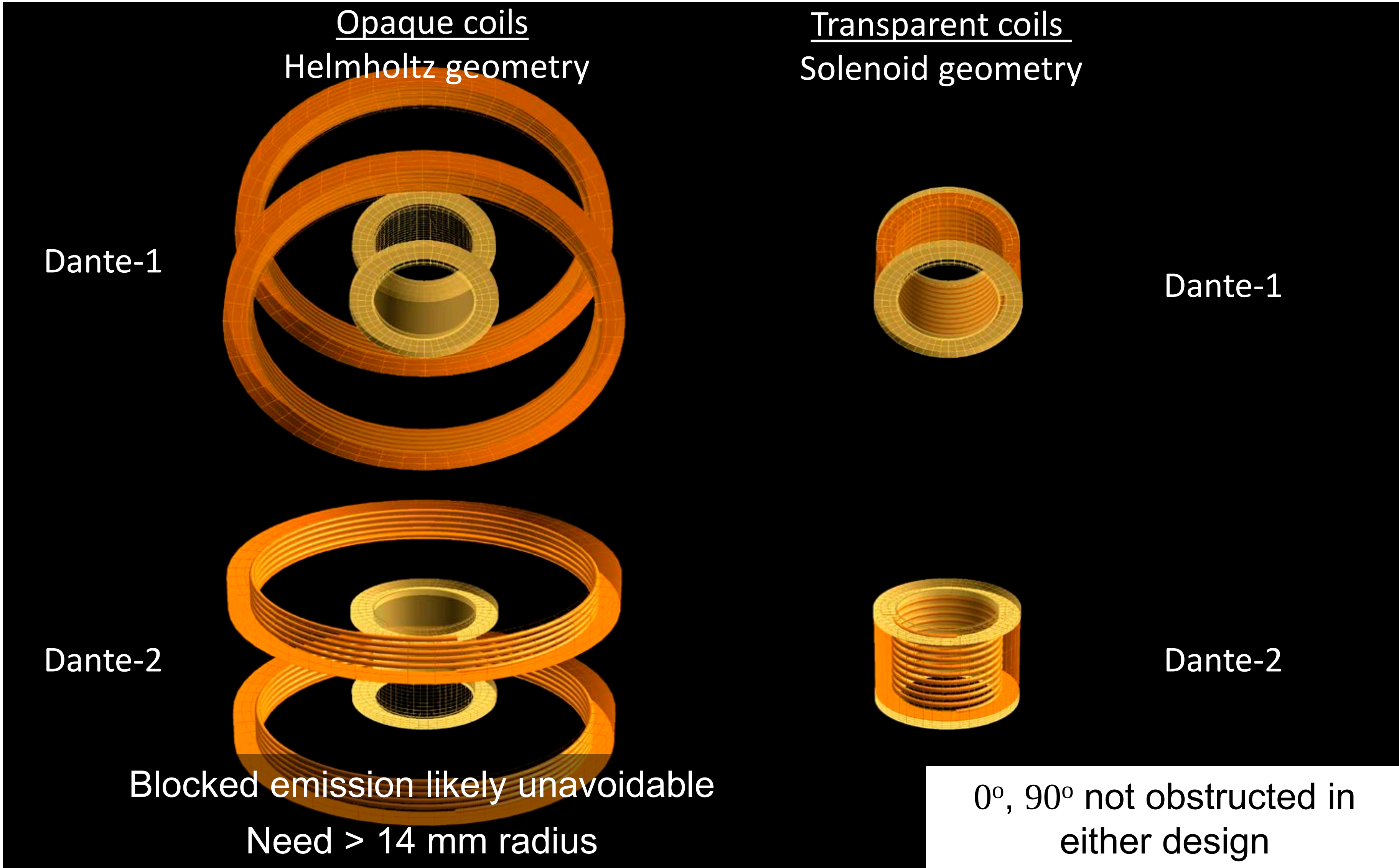
Epperlein-Haines/Lee More

Observe melting when…

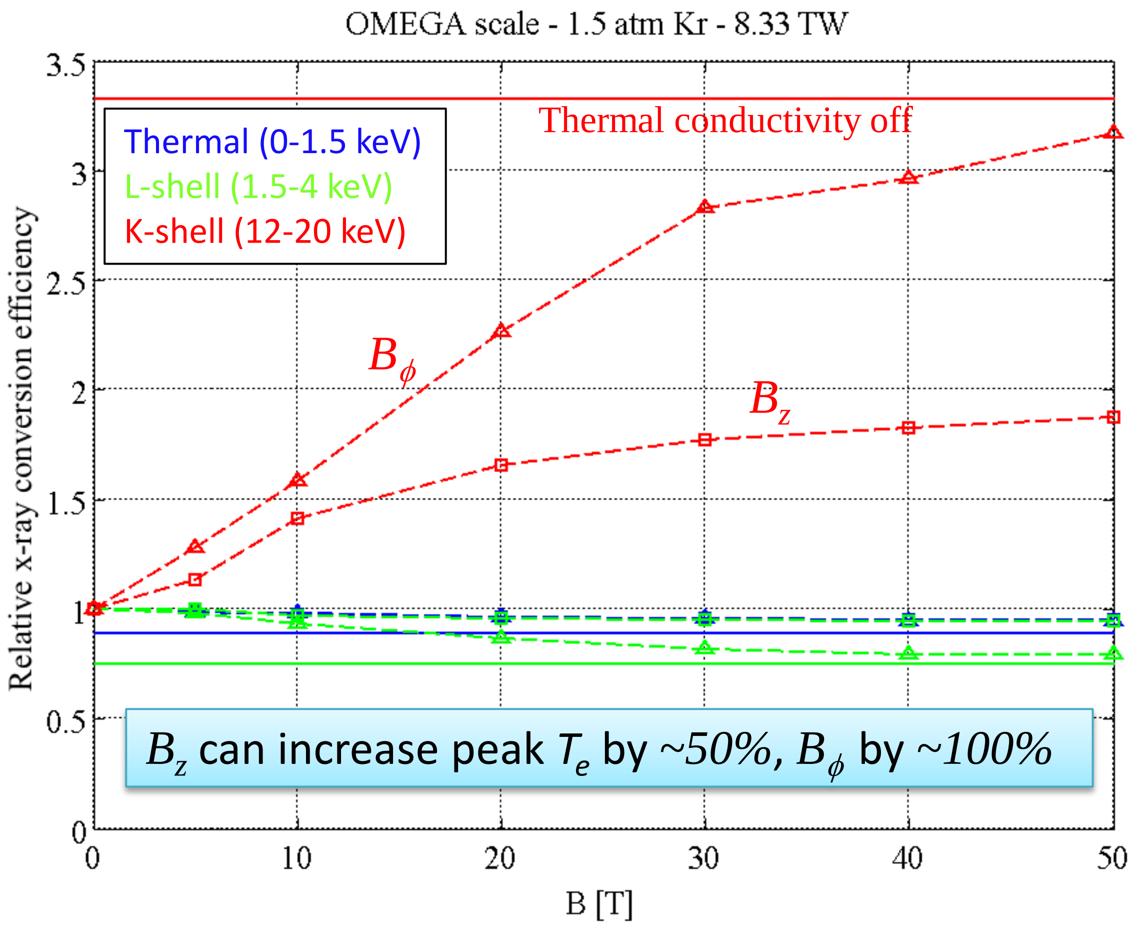
$$t_{melt} \approx \frac{\tau^2}{10}$$

$$\tau_{melt}^{MHD} \approx \boxed{10\,\mu s}$$

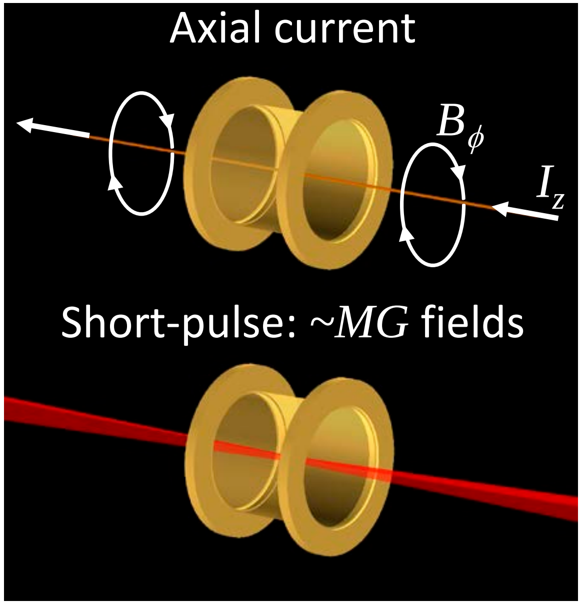
This experiment requires diagnostic access for Dante, NXS, GXD and SS-II



Alternatively, B_ϕ can provide both radial *and* axial insulation



May be possible to achieve nearly total thermal insulation with $B_\phi \sim 30\text{-}50\ T$



No line-of-sight issues

Laser-driven fields likely less uniform than current-driven

Harder to get ~$10\ T$ fields with single wire

Other issues

Machine safety considerations (debris, laser damage, backscatter, diagnostic damage risk, etc)

- Likely reduced backscatter risk from enhanced Landau damping at increased temperatures
- Increased debris risk with Helmholtz coils

There aren't currently any vetted diagnostics/calibrations for Ag K-shell measurements

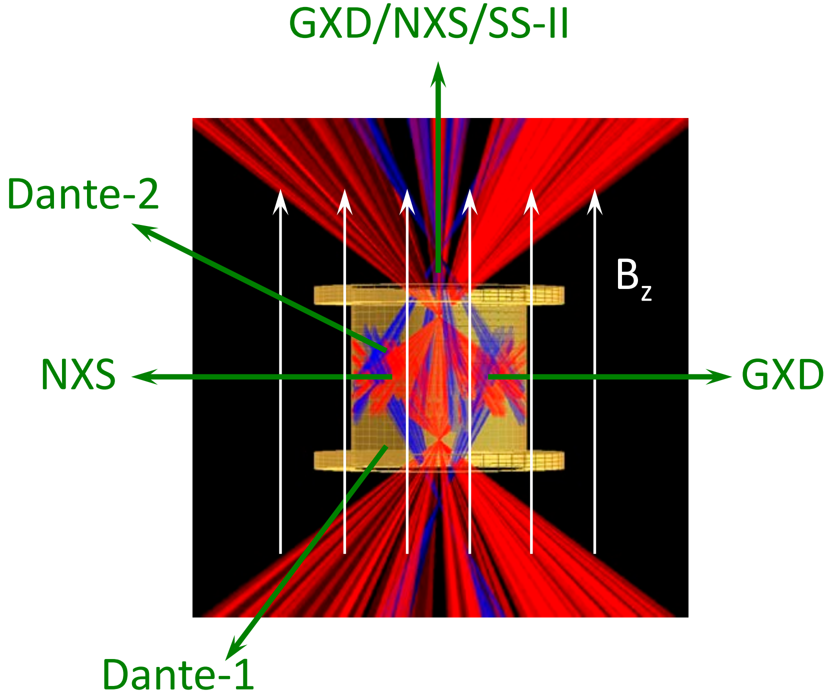
Summary

Experiment: Enhancing multi-keV x-ray sources with B-fields

Summary requirements

B-field magnitude	*10 - 50 T*
B-field spatial shape / extent	**Helmholtz or solenoid field shape,** *0.25 cm³*
B-field uniformity	*25%* **over the required volume**
B-field rise time	*>10 μs*
Diagnostic access	**NXS, GXD, SS-II, Dante**
Other	**None**

Summary experiment sketch



2 page Physics summary (1)

Experiment: Magnetized preheat for MagLIF using 20-30 kJ

Experiment: MagLIF on NIF
Responsible Org: LLNL/SNL
NIF shots from: Program
Shot RI: Name of person
Engineer: Person / organization

Experimental objectives:
Measure effect of B field on plasma temperature and lifetime

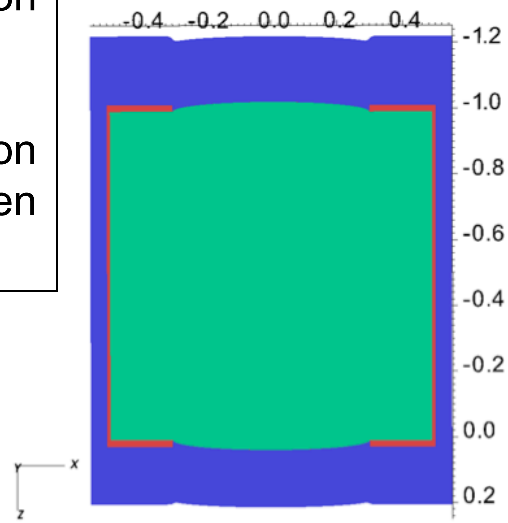
Key physics related to having a B-field: Suppress thermal conduction losses of preheated plasma

Expected results: Increased electron temperature during preheat phase when $\omega\tau>1$, and increased plasma lifetime

Important aspects of the experiment:

- **30 T peak field, ≤ 30% uniformity (future goal ≤ 10%)**
- **Available for shots in 18-24 months**
- **Can be done in phased approach starting at 10 T, but data return and results improve with higher field**

Summary experiment sketch



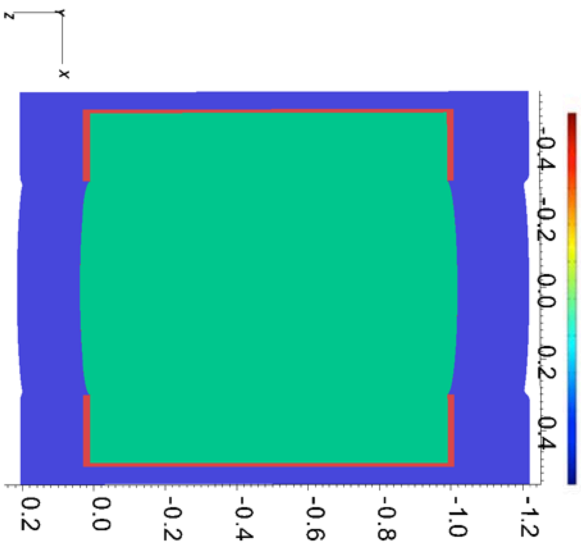
- **1 cm long by 1 cm diameter gas pipe**
- **100 μm thick beryllium (or 75 μm CH?)**
- **0.5 μm thick polyimide windows on both ends**
- **Laser focused to center of pipe**
- **Standard NIF inner beam phase plate, 1.2 x 1.65 mm minor/major diameter**
- **3 TW of 3ω light, 24 kJ over 8 ns**
- **Peak 1.93e14 W cm^{-2} at best focus**
- **Gas fill: 1 atm of C_5H_{12} at room temp., compare to 0.5 atm fill with same windows**
- **FUTURE: High-pressure magnetized DT**

2 page Physics summary (2)

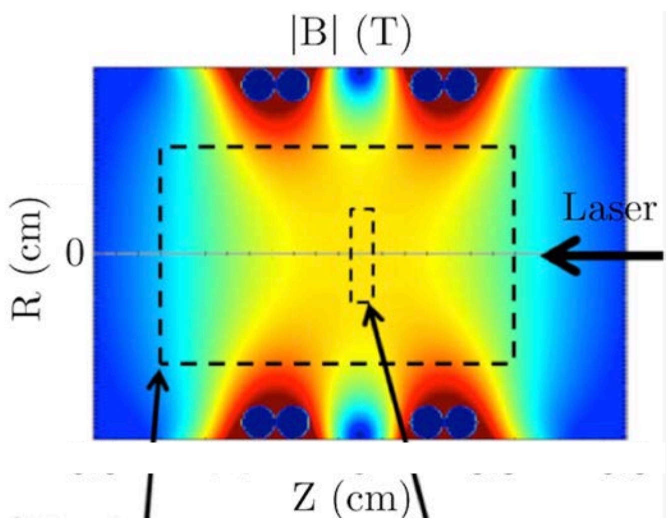
Experiment: Magnetized preheat for MagLIF using 20-30 kJ

More detailed experimental sketch showing:

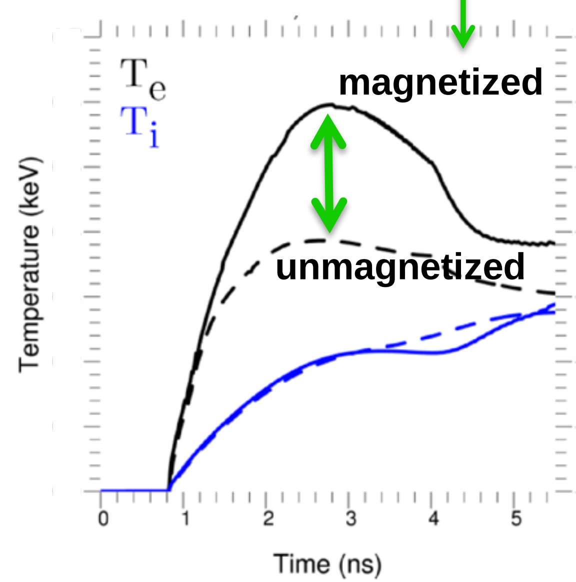
- One quad of NIF, single-sided illumination; B-field along laser axis
- Key diagnostics: x-ray framing camera, pinhole camera, spectroscopy
- We seek to measure the difference in T_e with vs. without B_z field (see Fig.)
- We seek to measure propagation distance (size of preheated plasma)



EXAMPLE



EXAMPLE



This experiment requires a $B_z \geq 10$ T and uniformity to $\leq 30\%$

B-field magnitude : 10 T initial, 30 T desired

B-field spatial variation requirements : Solenoidal or Helmholtz field

B-field spatial uniformity requirements : ≤ 30 % initial, ≤ 10 % desired

- Required B_z spatial uniformity required for integrated (neutron-producing) MagLIF is a work-in-progress. About 1% was achieved at Z, but this value is not known to be required.

This experiment requires a magnetized volume of ~0.8 cm^3

Approximate magnetized volume : Cylinder with V ~ 0.8 cm^3

(ICF target limit: D = 1 cm, L = 1 cm, V = 0.785 cm^3)

Spatial shape of magnetized region : Cylinder

Proposed source current path for achieving this :

Helmoltz configuration to provide better diagnostic access to the main gas-pipe plasma

This experiment requires the field to turn on no faster than 24 μs (10 T) or 73 μs (30 T)

Rise-time determined by need to fully diffuse into target without deforming or otherwise compromising target integrity.

Target tube thickness attenuates x-ray signal, so it (and its Z*) should be minimized.

For 30 T peak field and 100 μm thick *Be* gas pipe tube: ≥ 73 μs

For 10 T peak field and 100 μm thick *Be* gas pipe tube: ≥ 24 μs

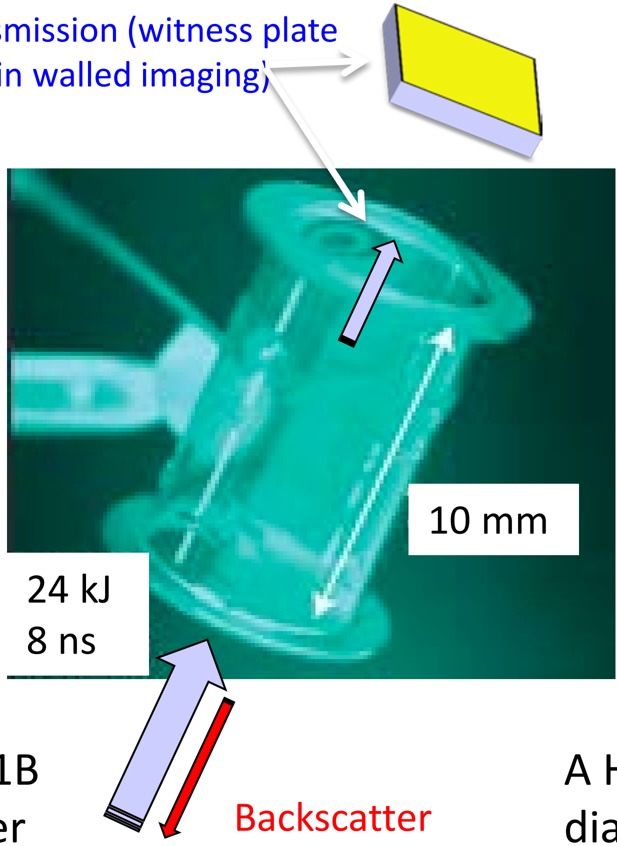
For ≤ 30 T peak field and CH gas-pipe: ≥ 2 μm (or driven by the heating rate in the pulsed-power delivery

- Possibility for ~30% reduction with ~70 μm thick *Be*?
- Possibility for reduction if tubes use thin CH, SiO_2, etc., instead
- Future target designs may involve small amounts of higher-Z metal layers/contaminants for mix studies, but unlikely to raise requirement much

This experiment requires diagnostic access for these measurements…

- Measure transmission, backscatter and Te
- Single quad, CPP, SSD, PS, 24 kJ in 8 ns: ~ 2×10^{14} W/cm^2
- 2 shots: n_e = 9×10^{20} cm^{-3} (10% n_{cr}) and 4.5×10^{20} cm^{-3}

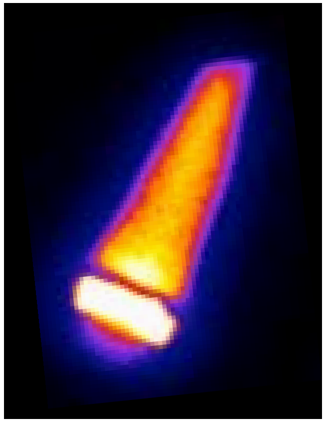
Transmission (witness plate or thin walled imaging)



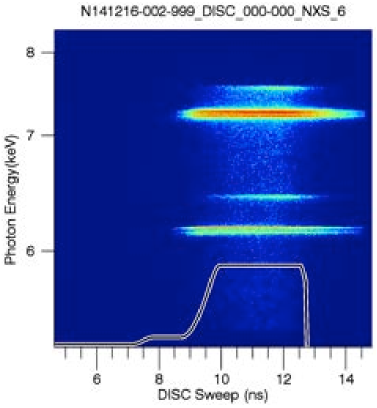
Q31B laser

Backscatter

Gated camera image (expected)



Spectroscopy data for Te (notional)



A Helmholtz field configuration provides the best diagnostic access for this experiment

Single-quad experiment will require it's own debris consideration

Machine safety - debris:

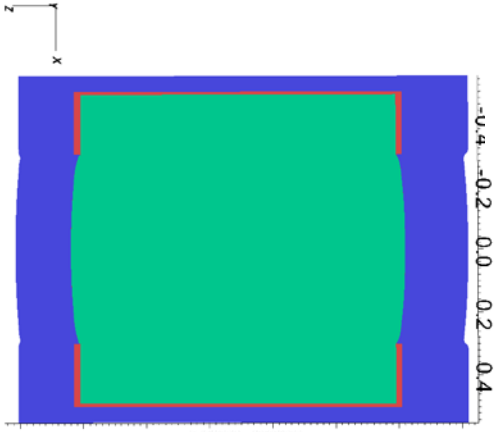
The experiment is a single quad (≤ 30 kJ). This low energy may create particle debris. Need to evaluate or consider "destroyer-pulse"

Experiment: Magnetized preheat for MagLIF using 20-30 kJ

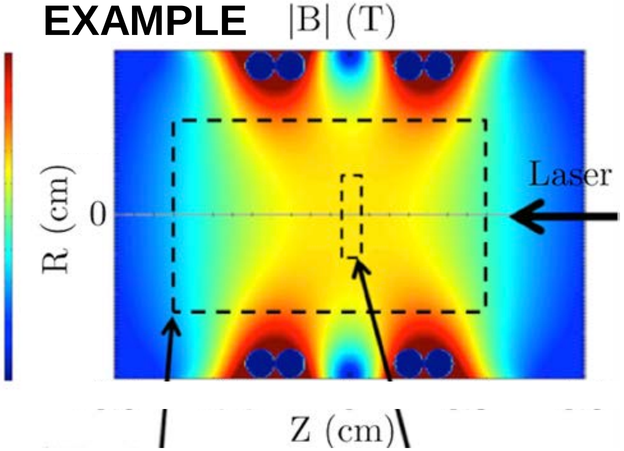
Summary requirements

B-field magnitude	**10 T - 30 T (goal)**
B-field spatial shape / extent	**~0.8 cm^3; Solenoidal or Helmholtz field**
B-field uniformity	**≤ 30% (initial) over required volume (≤ 10% goal)**
B-field rise time	**≥ 24 μs (to ≥ 73 μs)**
Diagnostic access	**X-ray spectroscopy at several positions**
Other	**Target body material? (Assumed *Be*)**

Summary experiment sketch



EXAMPLE



2 page Physics summary (1)

Experiment: Magnetized PDD

Experiment: MagPDD
Responsible Org: LLE
NIF shots from: Program
Shot RI: Hohenberger, TBD
Engineer: TBD

Experimental objectives: PDD ICF w/ magnetic-flux compression to reduce electron heat flux losses

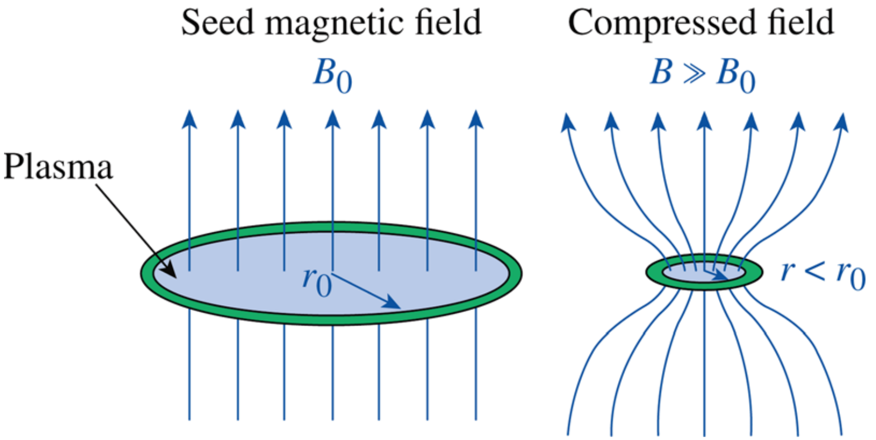
Key physics related to having a B-field: embedded B field is trapped in the ionized gas inside the capsule, undergoes magnetic flux compression

Expected results: heat flux reduction due to electron confinement along B-field lines and enhanced hot spot temperatures and yield

Important aspects of the experiment:

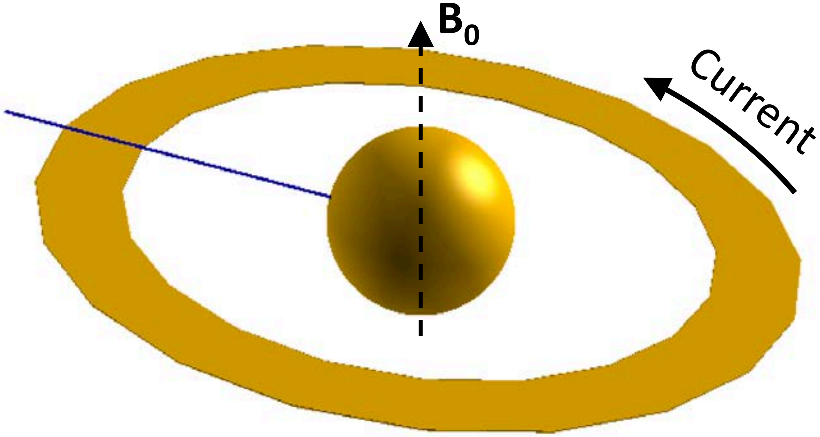
- **Has been demonstrated on OMEGA**
- **B ~ 10 T for electron heat-flux reduction**
- **B ~ 30 T to access α- and Triton-confinement (assuming ~500x amplification)**
- **Schedule - TBD**
- **Can the experiment be done as a phased approach – with phased increases in B? Yes**

Summary experiment sketch



Experiment: Magnetized PDD

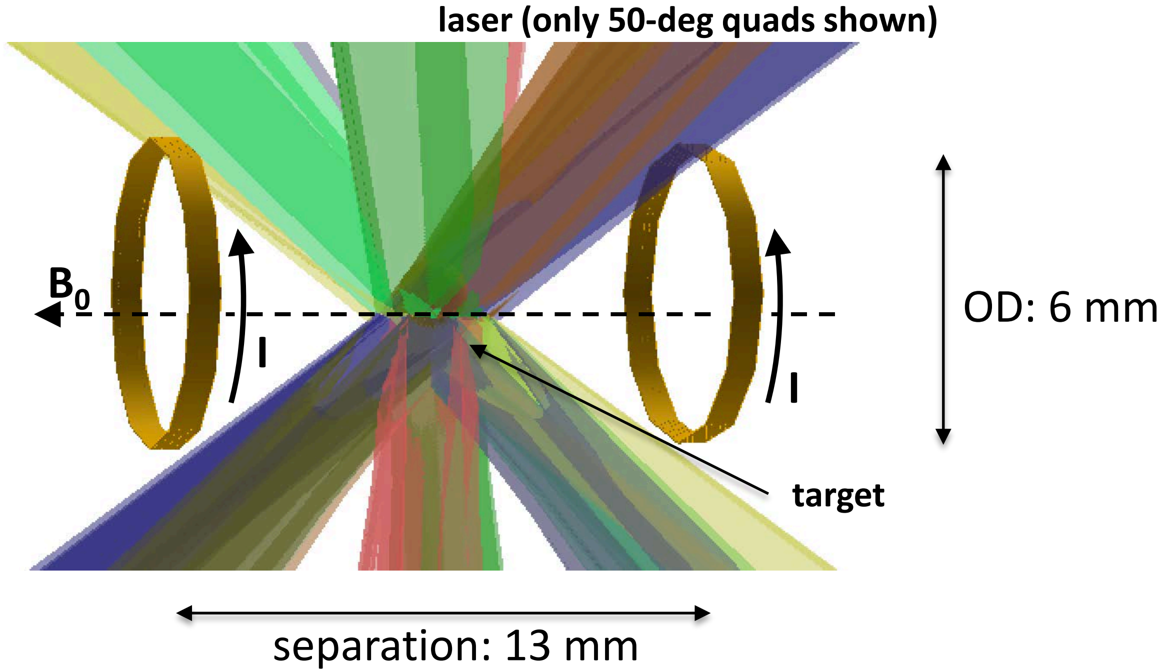
- Yield enhancement via magnetic flux compression has been demonstrated on Omega*
- Magnetic-flux compression on NIF allows to access hot spot regimes with reduced electron-heat flux and alpha- (DT) or triton- (D_2) confinement
- PDD is natural fit for coil in equatorial plane
- Coil with ~3.6 mm ID allows for unobstructed beam propagation with nominal PDD pointing (using 2.2 mm targets, and 5-deg coil tilt for target stalk)
- Experimental setup is based on current PDD implosion w/ standard diagnostics
  - GXD's
  - nTOF's
  - etc.

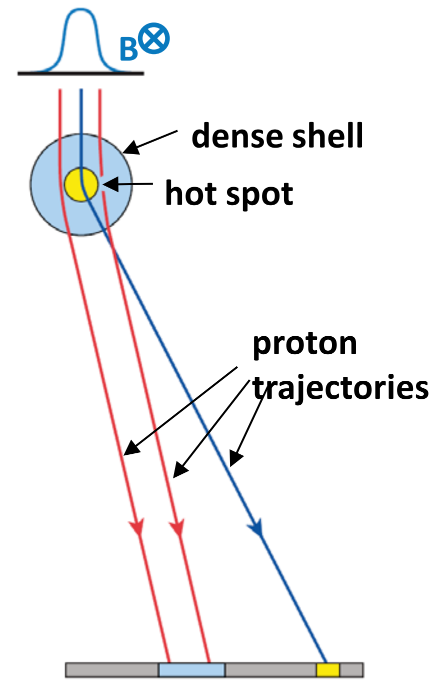


*M. Hohenberger *et al.*, Phys. Plasmas 19, 056306 (2012)

Experiment: Magnetized PDD

- Alternative configurations may also be considered
- "Helmholtz" coils allow better diagnostics access (e.g., proton radiography)
- Ellipsoidal hot spot in B_0 field direction enhances B-field effects by enhancing area perpendicular to the field lines, where heat losses are suppressed, good match for unique polar-drive geometry
- beam interference limits coil geometry





Electron heat-flux suppression requires B ~ 10 T over the capsule volume

- Electron-flux suppression has been demonstrated with seed fields of 8T on Omega
- For DT implosions, the 500x magnetic-flux compression of a ~20T B-field is sufficient to demonstrate alpha-particle confinement with $r_{gyro} < r_{hs}$
- For D_2 / warm implosions, a ~20-T seed is expected to confine Tritons to the hot spot
- Secondary yield enhancement in warm implosions from triton confinement has not been demonstrated before
- Volume set by minimum coil size and laser interference, ID ~ 3.8 mm for single-coil
- Rise time set by joule-heating quenching current rise, < 1 μs

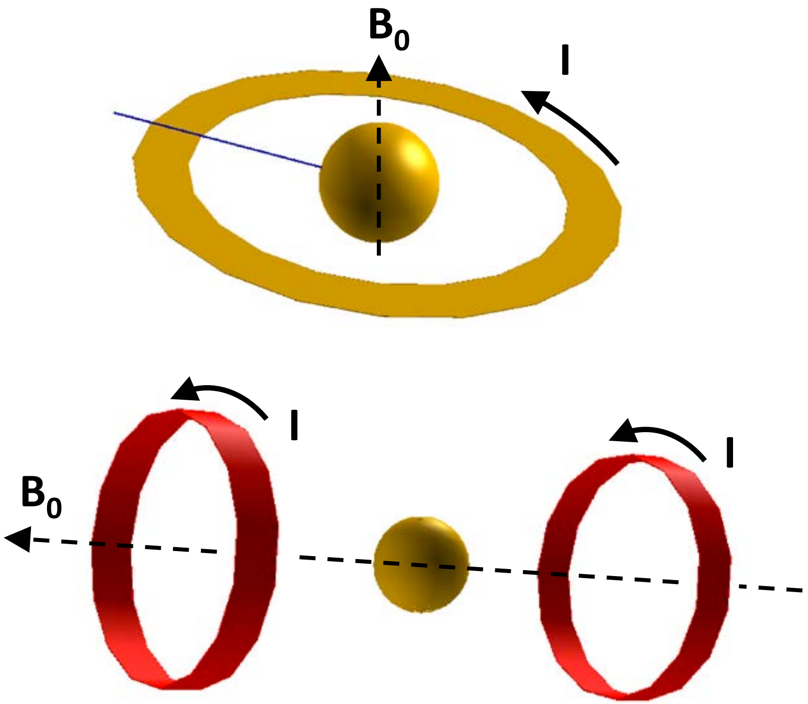
Summary

Experiment: Few word descriptive name of the experiment

Summary requirements

B-field magnitude	10 - 30 T
B-field spatial shape / extent	single coil, dimensions set by beam interference, ~3.6 mm ID
B-field uniformity	TBD
B-field rise time	<1 μs
Diagnostic access	nTOF line of sight
Other	None

Summary experiment sketch



Magnetized high energy-density plasma research at LLE

Collisionless shocks

Magnetic reconnection

Magnetized ICF

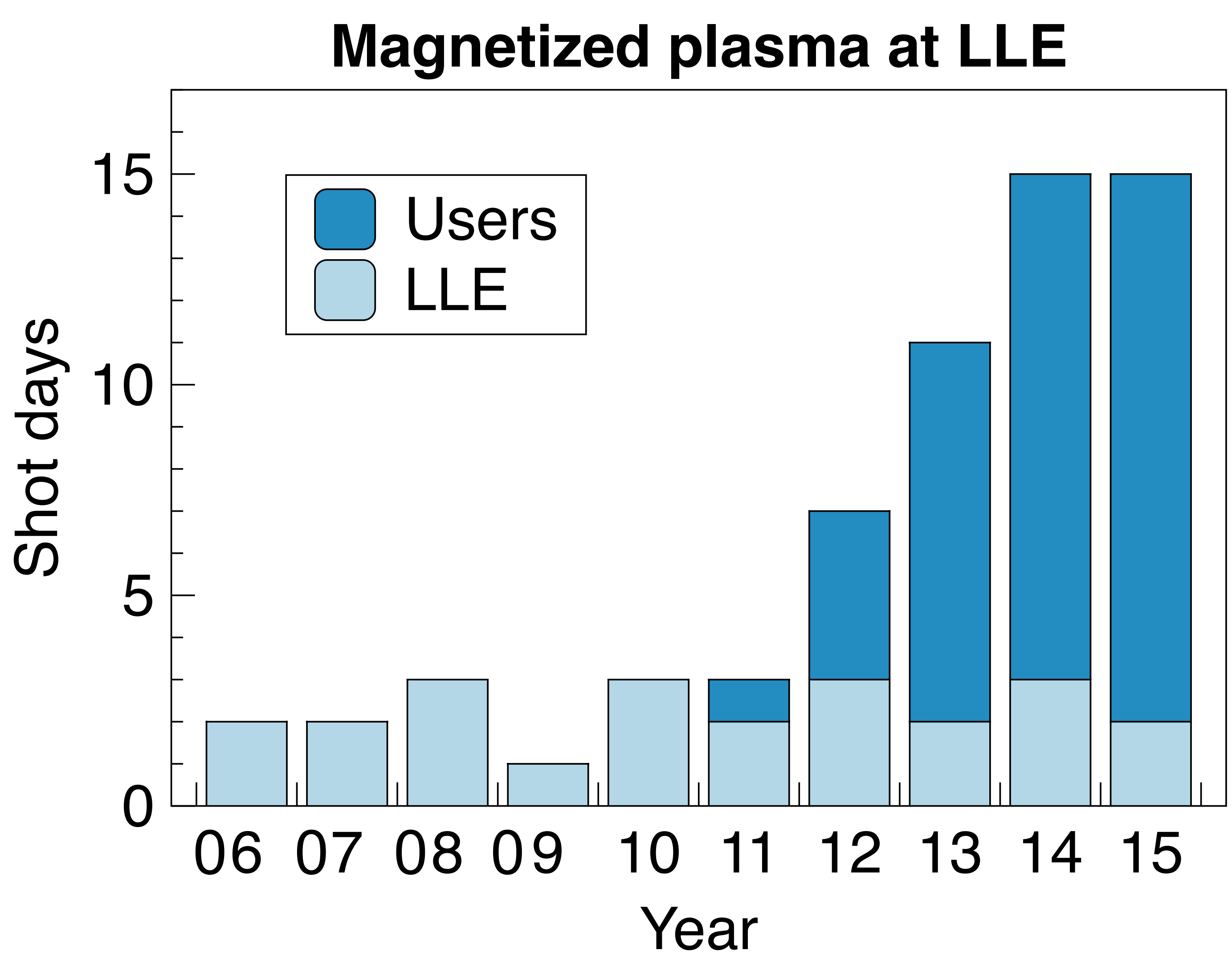
Magnetized liner

Pair Plasma

LPI in hohlraums

Magnetized jets

Astro-shocks



Gennady Fiksel

Bfield Workshop
Oct 12, 2015, LLLNL

Summary

MIFEDS has opened a new frontier on magnetized HED plasma research on OMEGA

- Magnetized HED plasma research has greatly expanded during the last few years
- Magnetic field generator MIFEDS has become a facility diagnostic, widely used by LLE and Users
- MIFEDS flexible platform allows for wide variety of experimental configurations both on OMEGA and EP
- New and exciting results have been obtained in the areas of ICF, astrophysics-relevant applications, e-e$^+$ pair production, and others
- Work ongoing on high-B platform development - from 10T to 30T to 50T

Collaborators

LLE Scientists:
O. Gotchev, J. Knauer, R. Betti, P.-Y. Chang,
M. Hohenberger, J. Davies, D. Barnak
S.X. Hu, P. Nilson

Engineers:
A. Agliata, W. Bittle, G. Brent, D. Hasset, L. Folnsbee,
D. Lonobile, M. Shoup, C. Taylor

Users:
W. Fox, A. Bhattacharjee, H. Chen, H.-S. Park, D. Montgomery,
and many others

Outline

- MIFEDS - platform for magnetized plasma studies
- Fusion and non-fusion applications
  - Field compression and neutron yield enhancement
  - Magnetic reconnection
  - Positron focusing
- Upgrade to higher B

The centerpiece for magnetized HED plasma research is MIFEDS

From an actual hallway conversation:

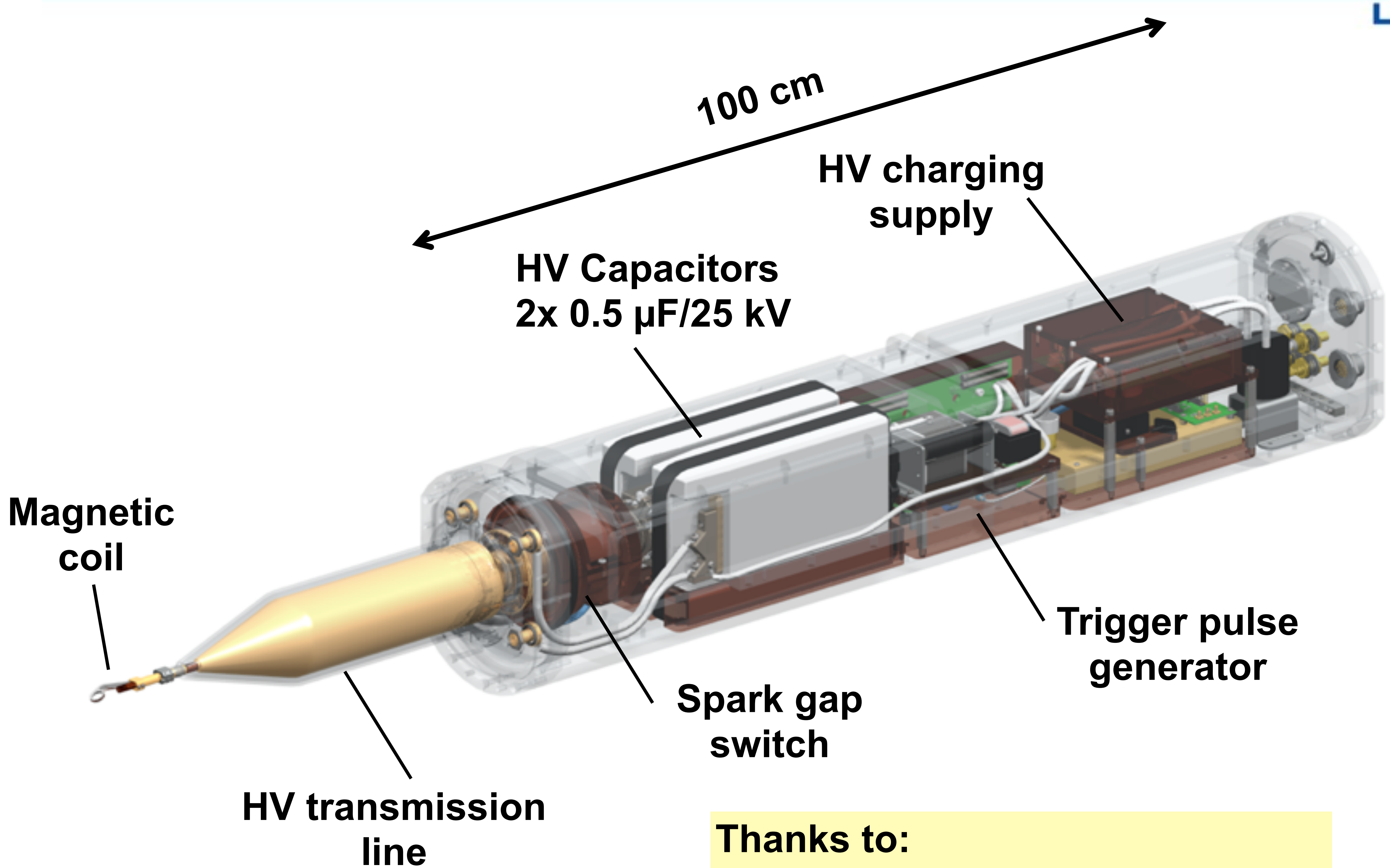
- Listen, I'm having problems with MIFEDS...

- Sorry to hear that. Maybe you should see a doctor..

MIFEDS
Magneto-Inertial Fusion Electrical Discharge System

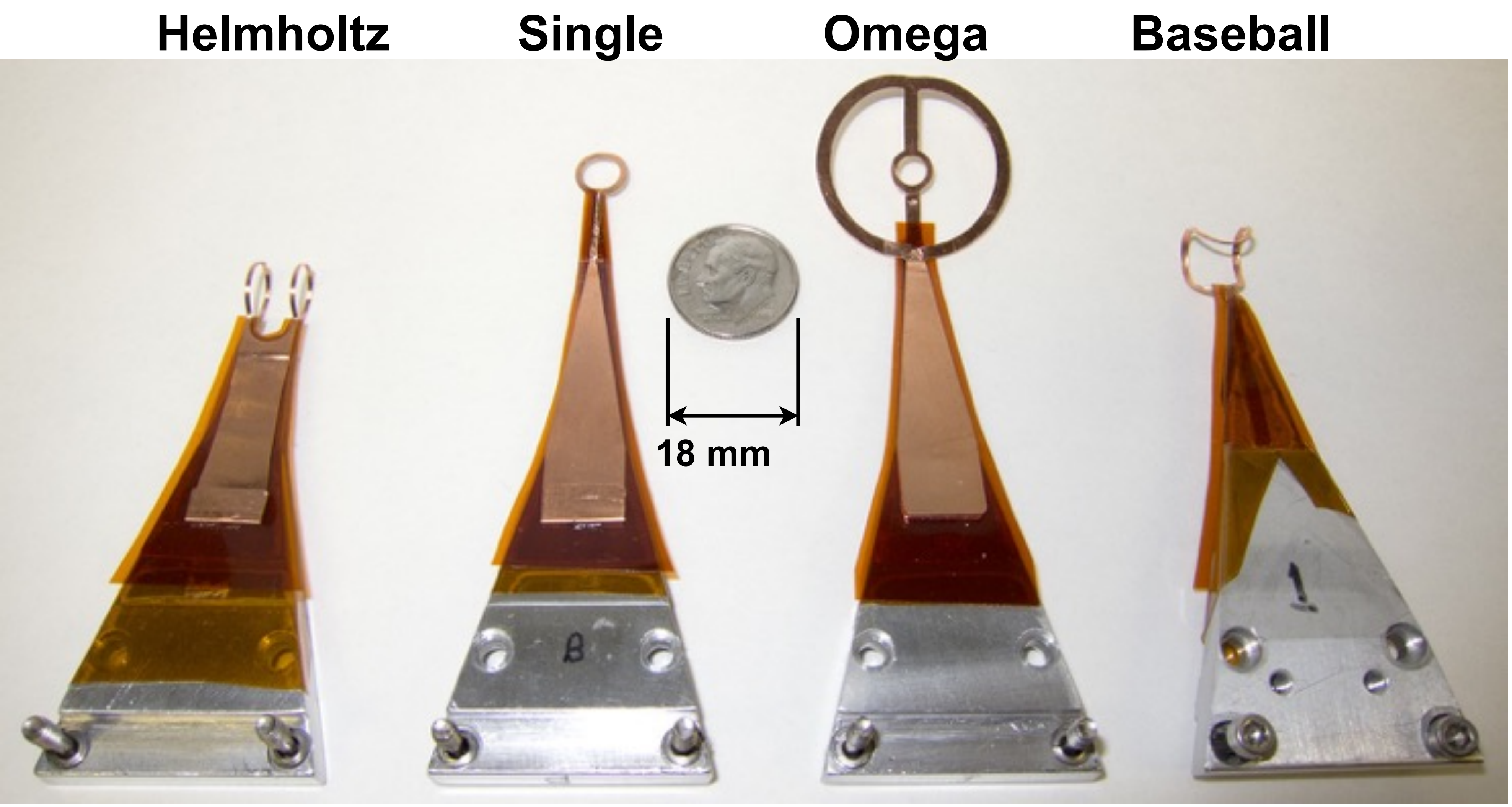
TIM-based generator of pulsed magnetic field

MIFEDS is a densely-packed assembly of high current, high voltage, and control electronics, all designed and engineered to be used in a TIM



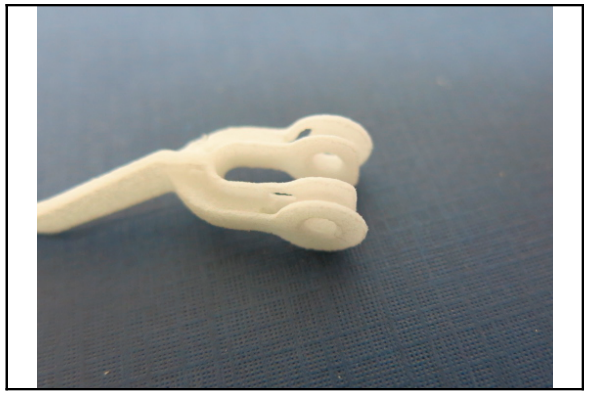
Thanks to:
C. Taylor, M. Shoup, D. Lonobile, D. Hassett, L. Folnsbee

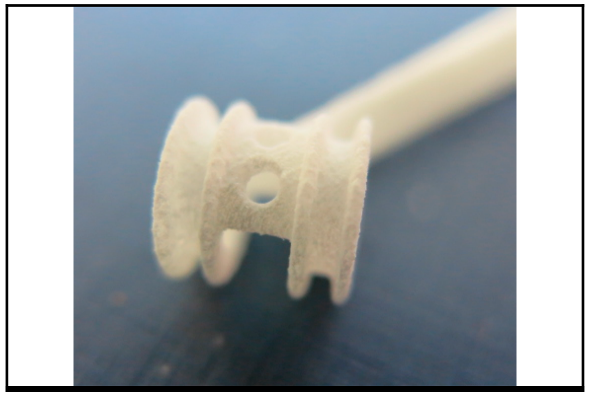
Historically, the coils were made by bending thin Cu foil and using Kapton sheets for isolation



Lately, we switched to 3-D printed magnetic coils allowing for a much wider variety of magnetic configurations

- The coils is made by winding a Kapton-insulated wire around a nylon coil form.
- The coil form is 3-D printed, which allows for virtually an unlimited number of possible precise configurations.



Two MIFEDS units operate on OMEGA and EP as facility diagnostics

- First deployment of these units on EP - August 2012, on OMEGA - November 2013
- Fields of ~10 T have been achieved in a ~2 cm^3 of effective B-volume with adequate beam and diagnostic access
- The device has become user friendly and reliable
- We had one campaign on positron focusing on TITAN (with some alignment issues)

	Stored Energy	Current/ Time to peak	Bfield	B Energy	Comments
MIFEDS 10T now	200 J	30kA/0.5μs	10 T	100 J	TIM, single pulse use

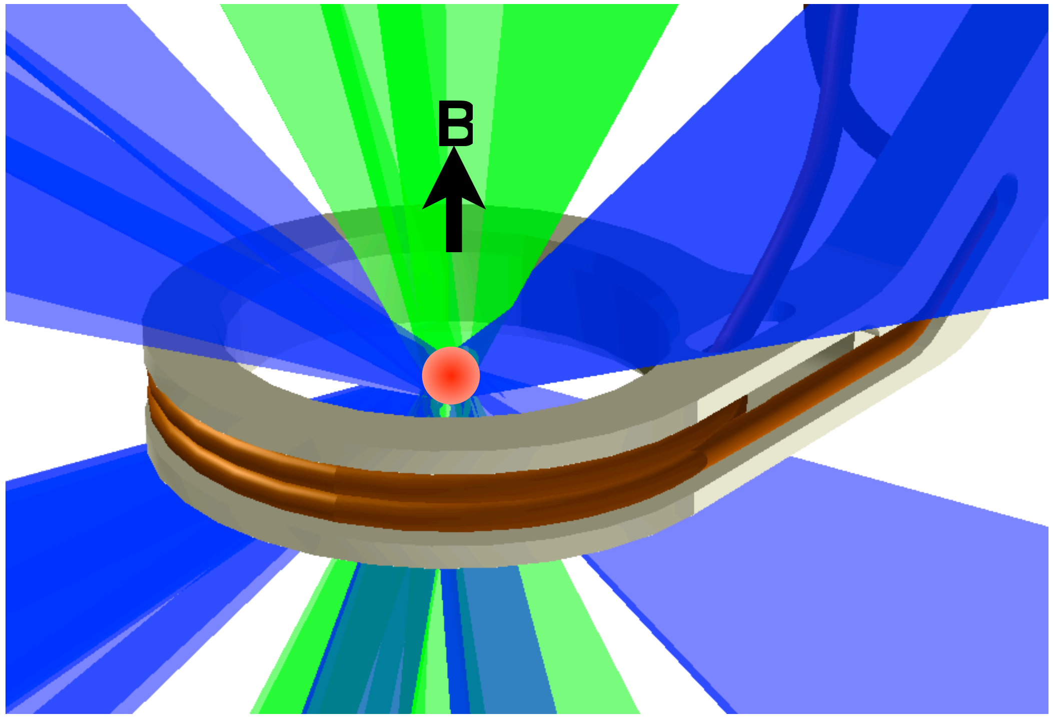
Outline

- MIFEDS - platform for magnetized plasma studies
- **Fusion and non-fusion applications**
  - **Field compression and neutron yield enhancement**
  - **Magnetic reconnection**
  - **Positron focusing**
- Upgrade to higher B

Fusion enhancement - magnetization of plasma electrons inhibits the conduction heat transport

- Plasma electrons can be magnetized so the heat conduction losses are reduced and the temperature is increased

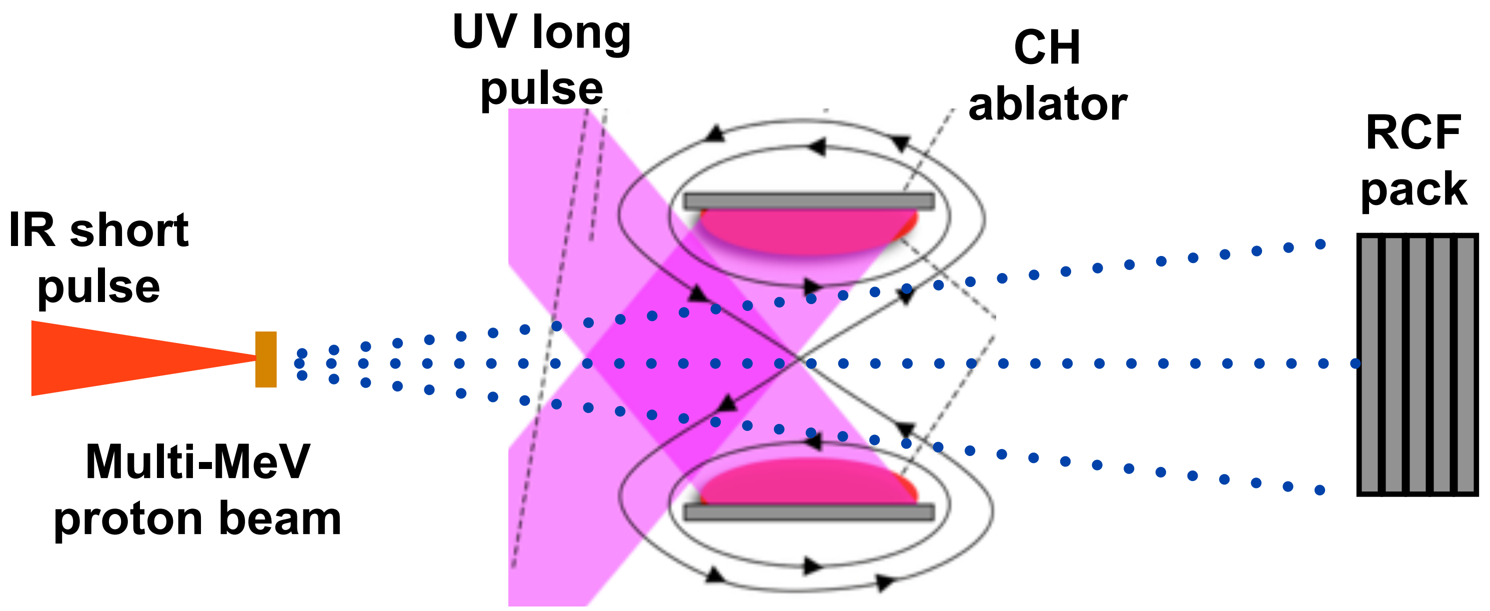
- Past results* - 30% increase in neuron yield, 15% increase in T_i

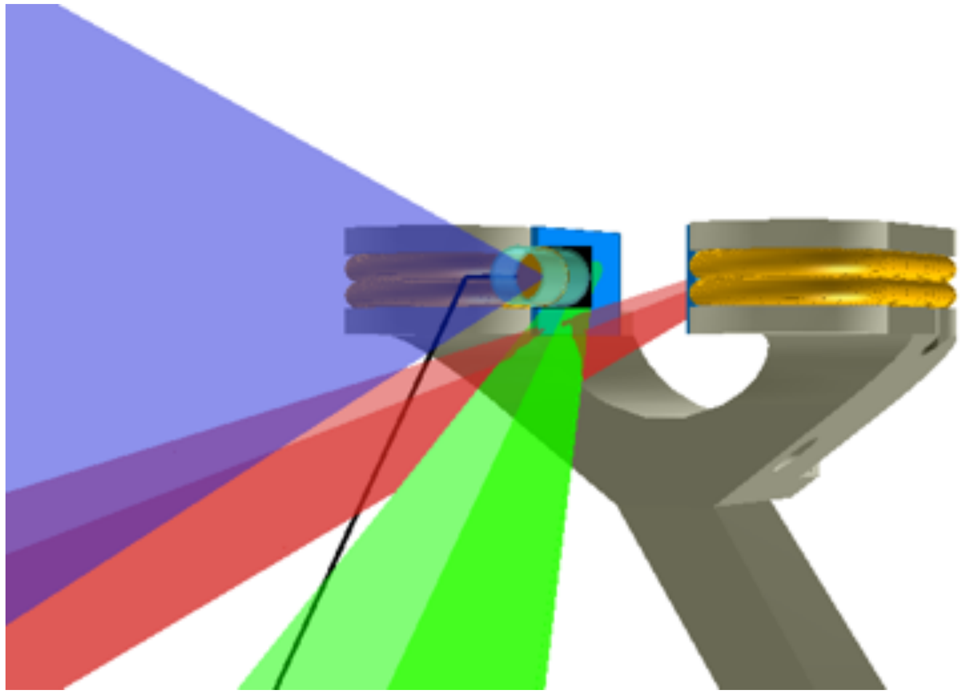


The topic is covered by M Hohenberger

* P.-Y. Chang et al., PRL 107, 035006 (2011)
M. Hohenberger et al., PoP 19, 056306 (2012)

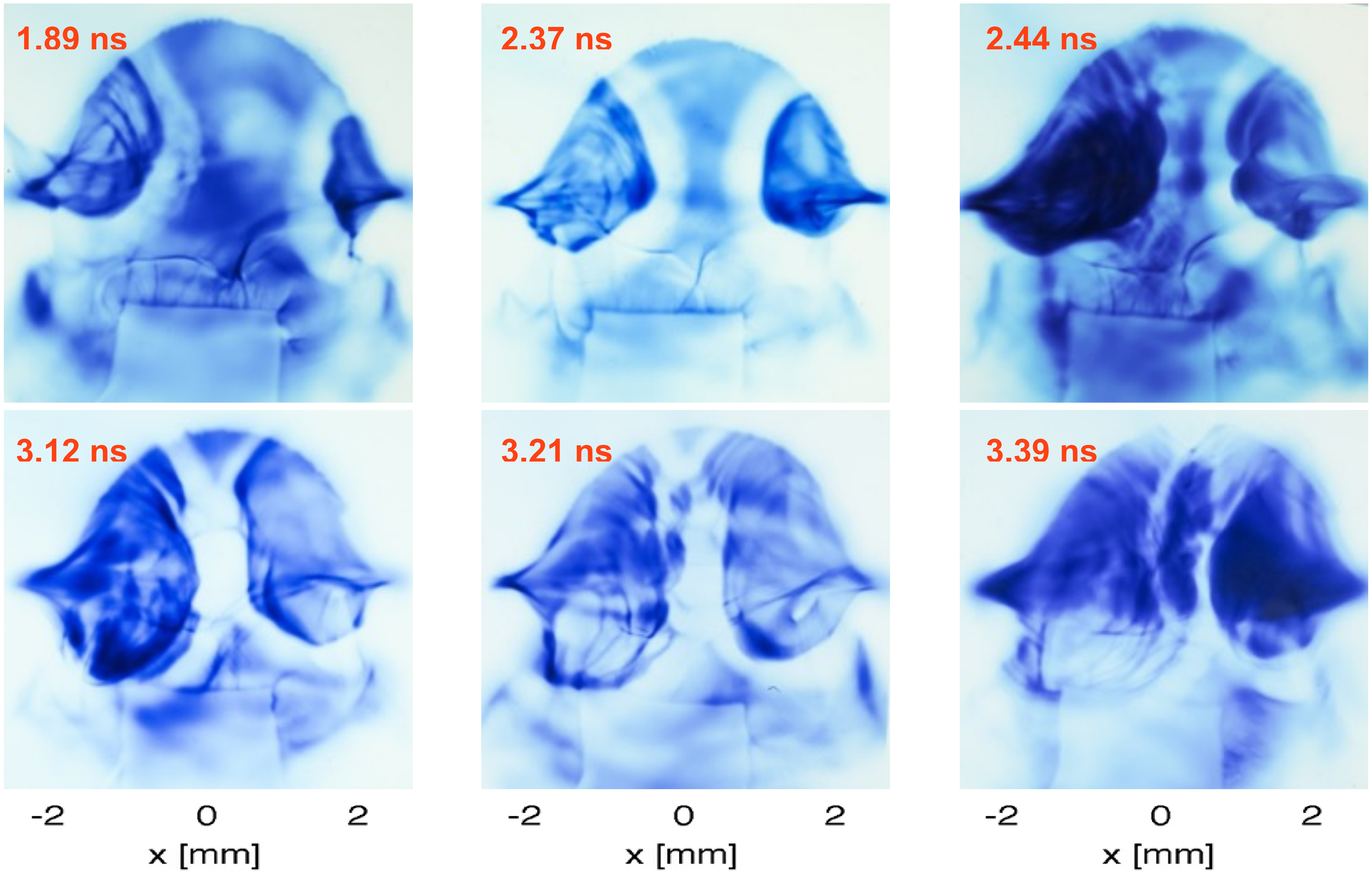
Reconnection of an external B-field was studied by colliding two HED plasma bubbles





B-field of 8 T was created by magnetic coils powered by MIFEDS

A series of proton (13 MeV) radiography images illustrates formation and collision of magnetic ribbons and creation of reconnected B-field

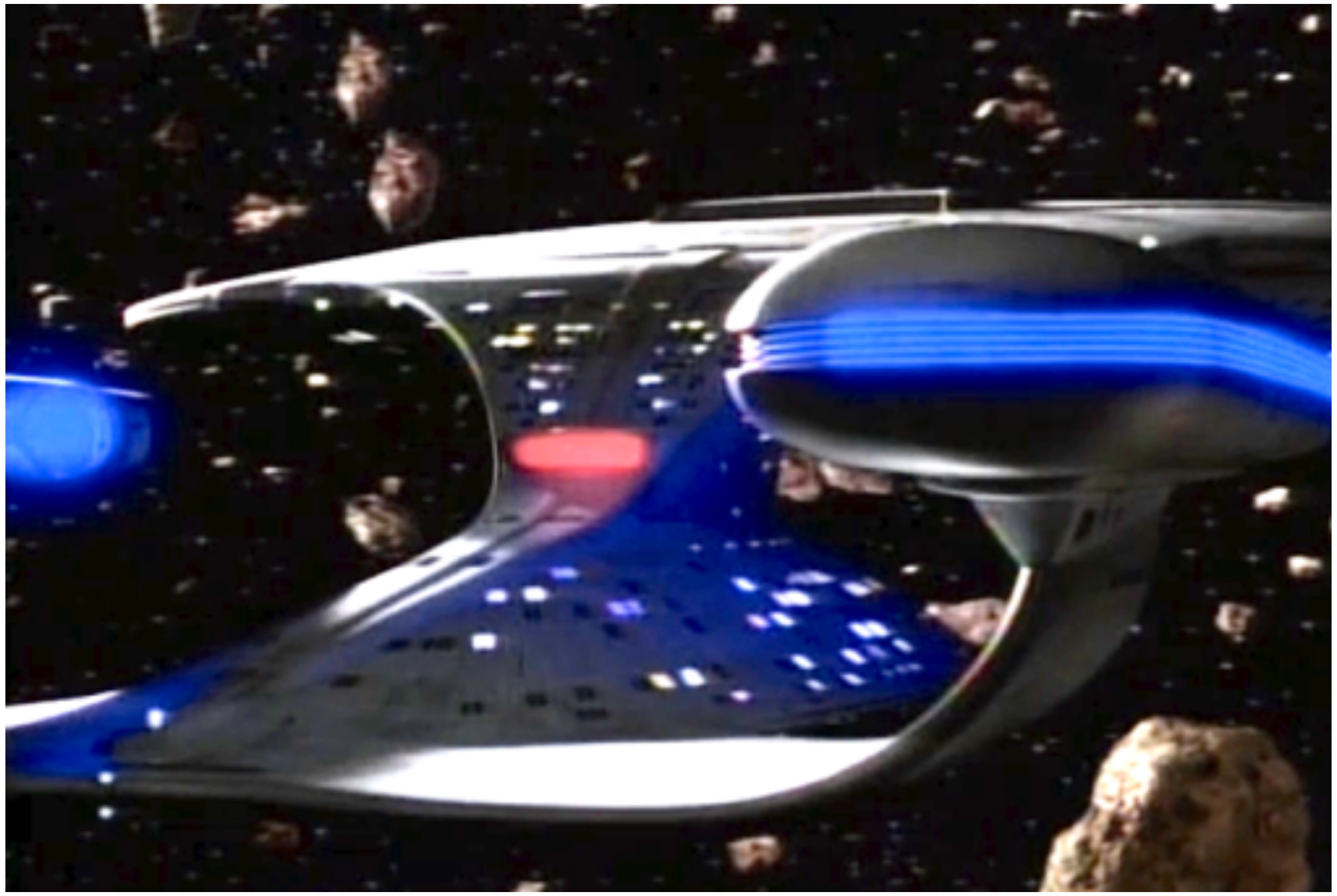


G. Fiksel et al., PRL 113, 105002 (2014)

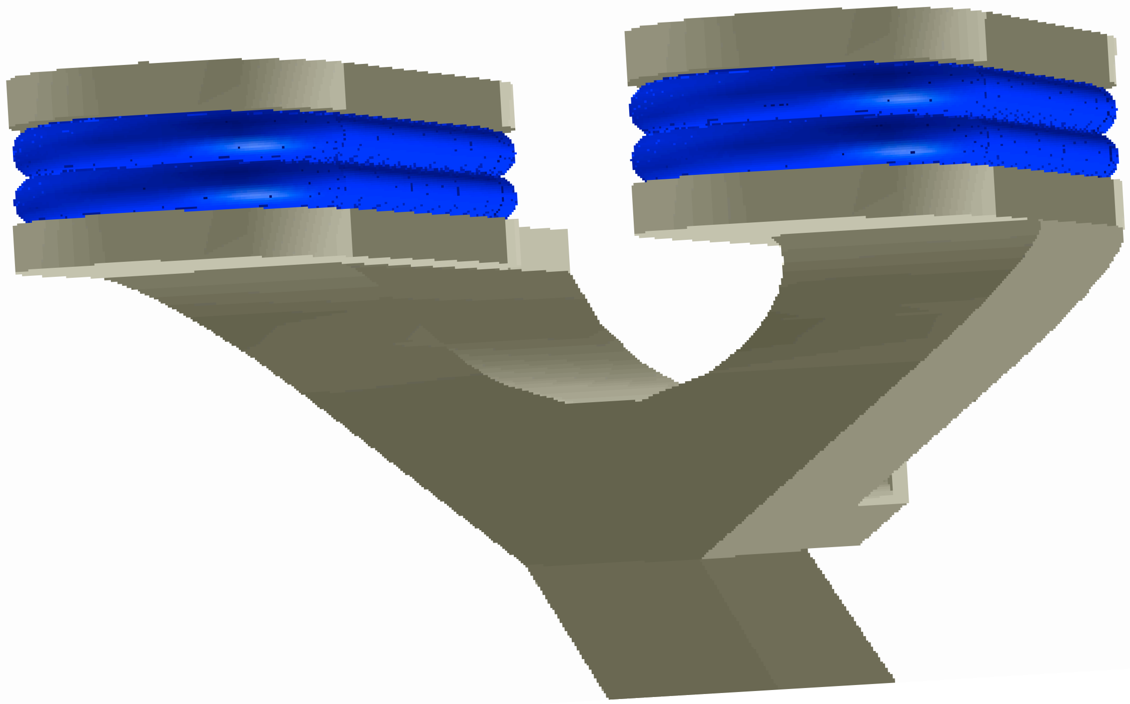
The topic will be covered is detail tomorrow by W. Fox

We call the reconnection coil - “Enterprise”*

USS Enterprise
Star Trek TNG

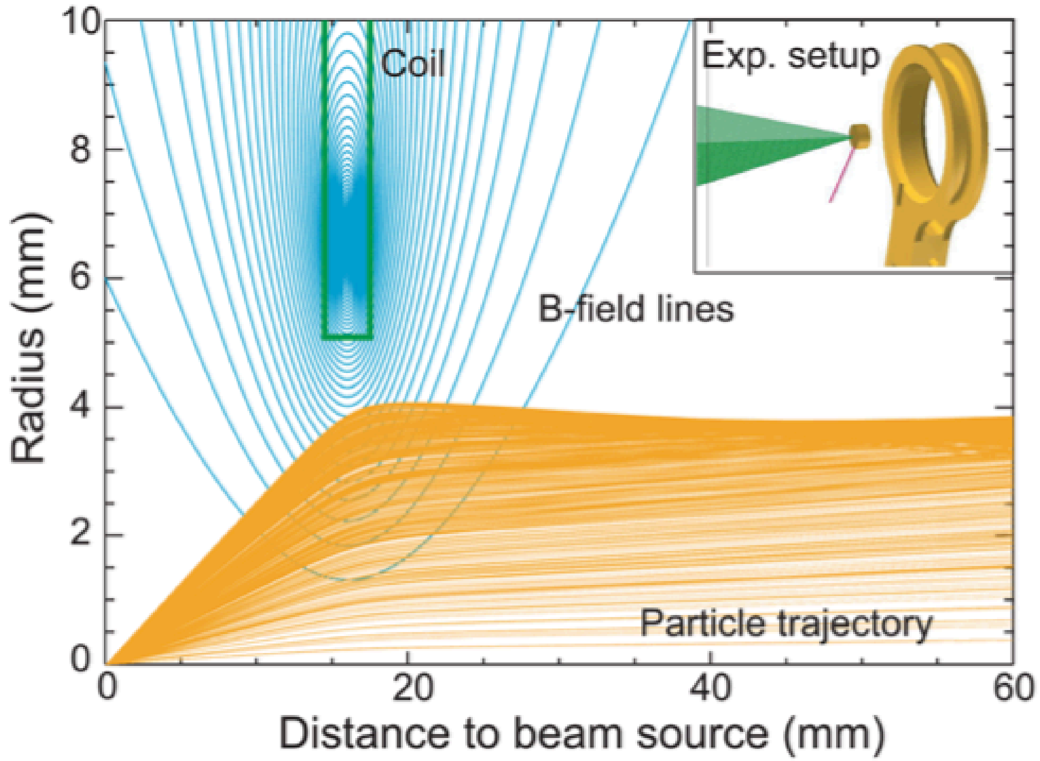


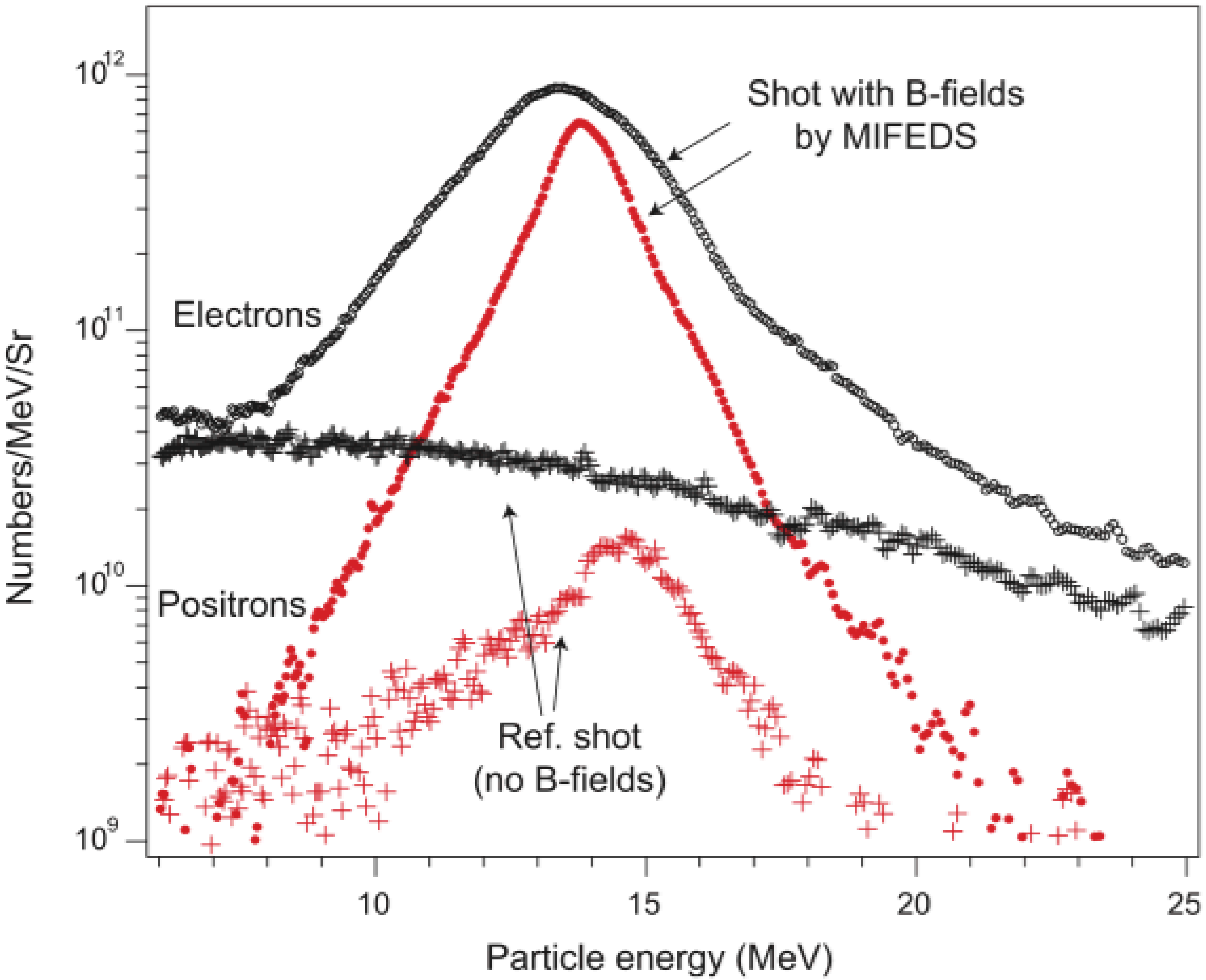
MIFEDS MagRecon
“Enterprise” coil



*Any resemblance is purely coincidental

Energetic positrons and electrons are focused with a magnetic lens





The topic is covered is detail tomorrow by H. Chen

Next step - positron trapping by MIFEDS TNG

H. Chen et al., PoP 21, 040703 (2014)

Outline

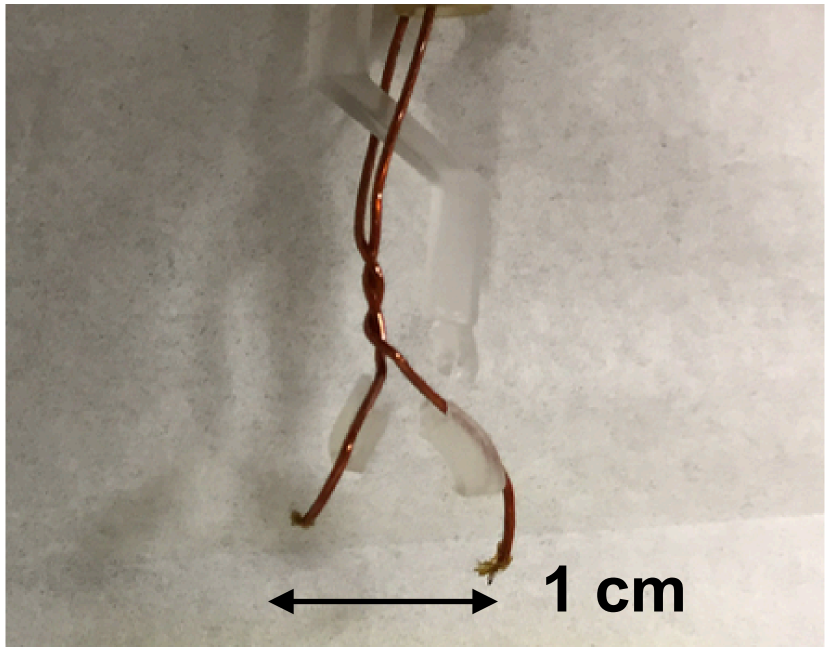
- MIFEDS - platform for magnetized plasma studies
- Fusion and non-fusion applications
  - Field compression and neutron yield enhancement
  - Magnetic reconnection
  - Positron focusing
- **Upgrade to higher B**

A high magnetic field is beneficial for many experiments - LLE and Users

- Fusion enhancement - spherical implosions, MAGLIF
- Magnetic reconnection - B (Lundquist)scaling
- Astrophysical shocks and jets - achieving P_{plasma}/P_{B} ~1

High B field is extremely challenging, especially in the high-power, precision optic laser environment

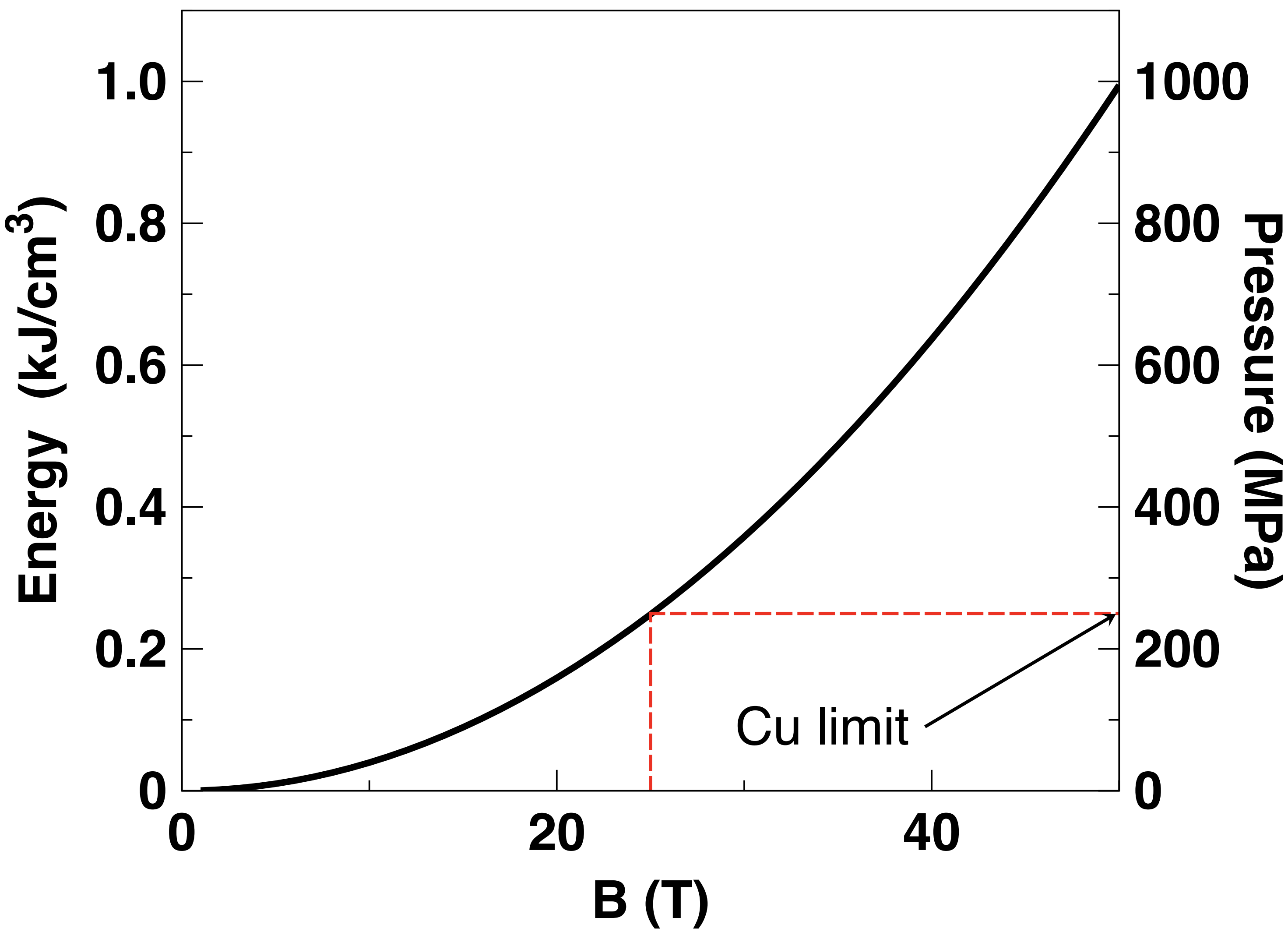
- High stored energy
- High mechanical stresses
- High thermal dissipation
- Arcing, debris, dust, EMI
- Beam and diagnostic access
- Coil explosion



MIFEDS

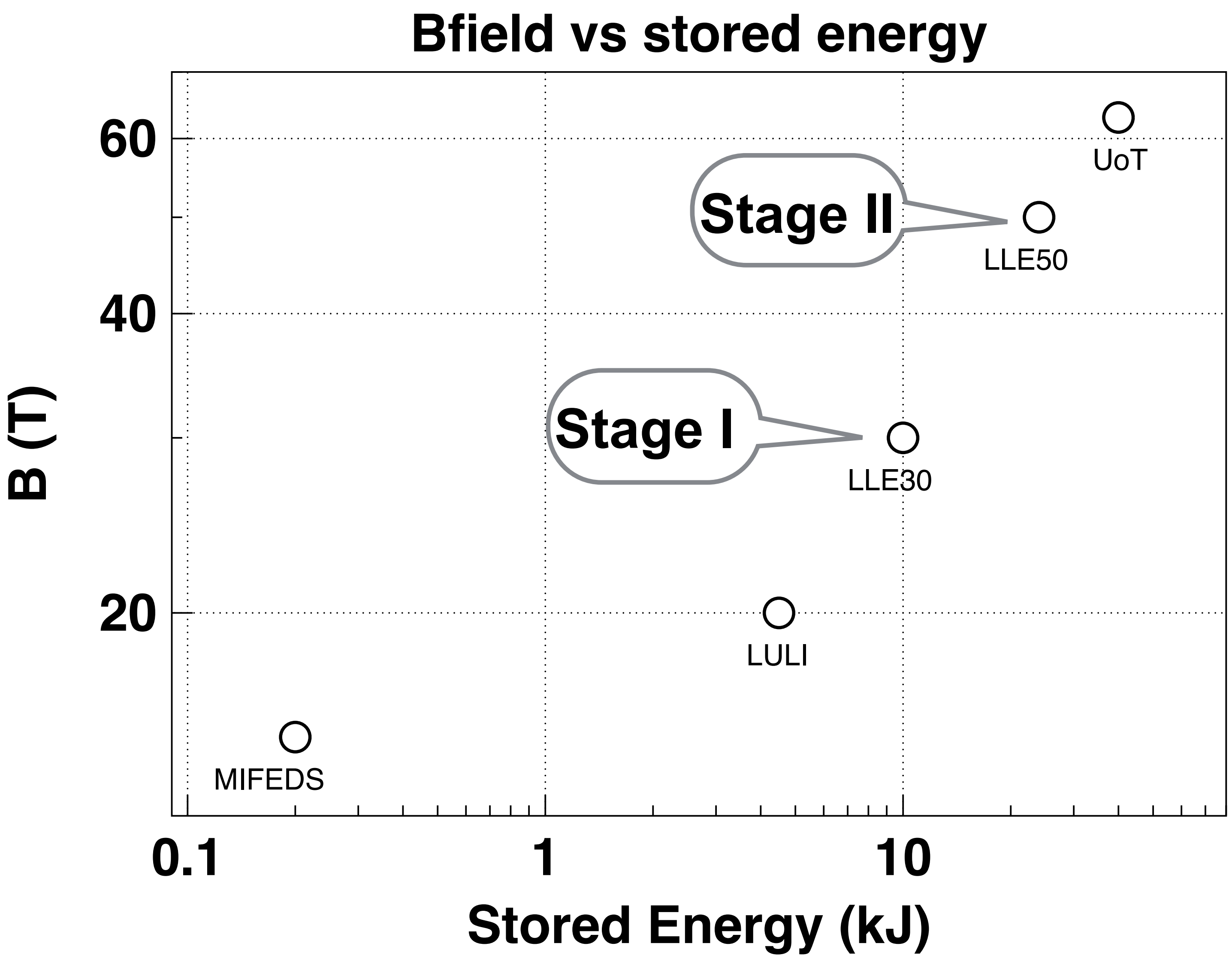
UoT

High B field requires high stored energy and results in high mechanical stresses which are ~B^2



- At 50T, B-pressure is 1000 MPa (10,000 atm)
- Copper ultimate tensile stress is 220 MPa => 25T-30T limit
- For short pulses ≤ 1μs, a coil can be free-standing - inertially supported
- For longer pulses, encasing is required

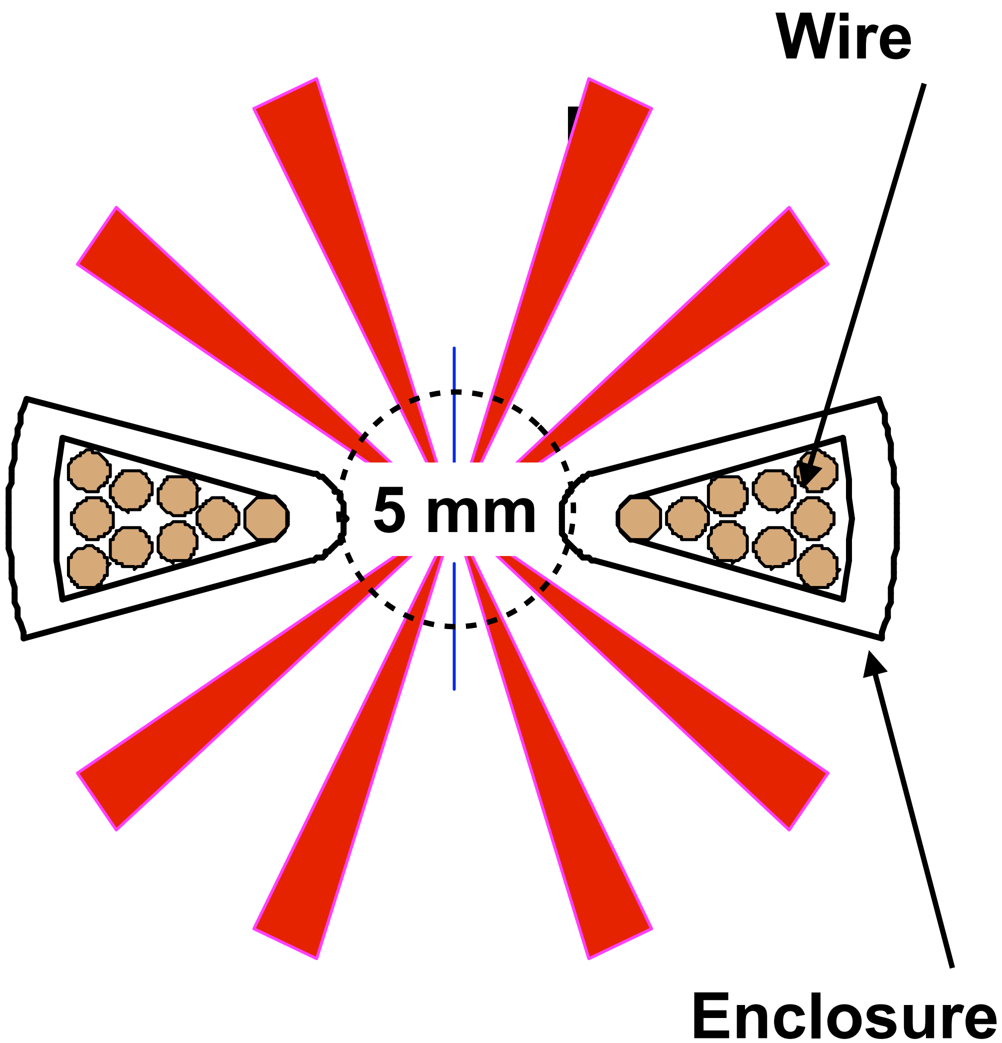
A staged development is proposed: Stage I - 10T==>30T, Stage II - 30T==>50T

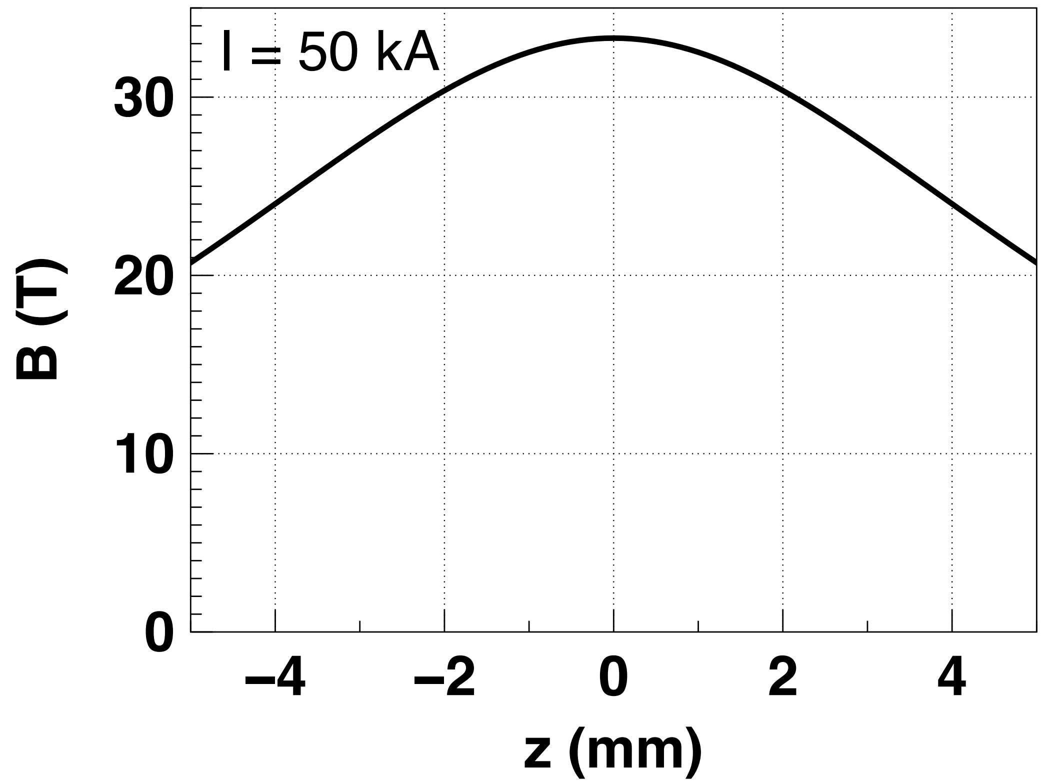


Good news - plasma beta, heat conduction, etc ~1/B^2

- **Current stage - 10 T**
- **Next stage 30 T, and order of magnitude increase in B^2, near the material stress limit**
- **Next stage 50 T, mechanical stresses and high thermal loading anticipated**

Possible coil design approach - multi-turn, encased. Requires 50 kA to produce 30 T in a ~5 mm dia volume

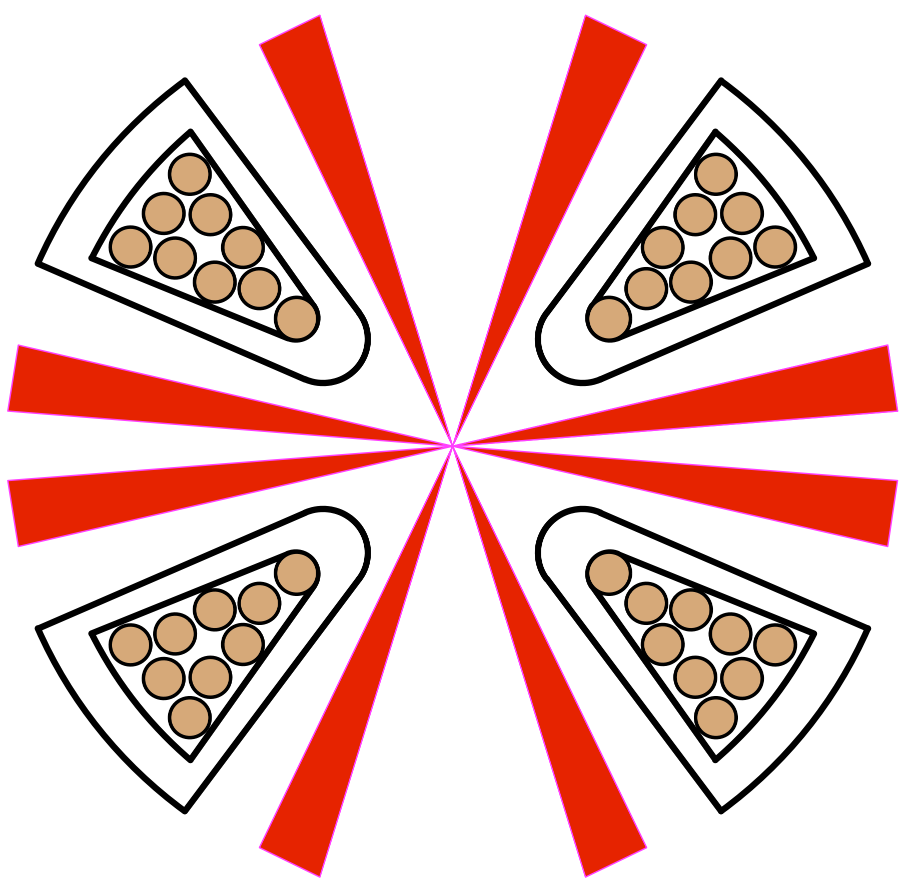




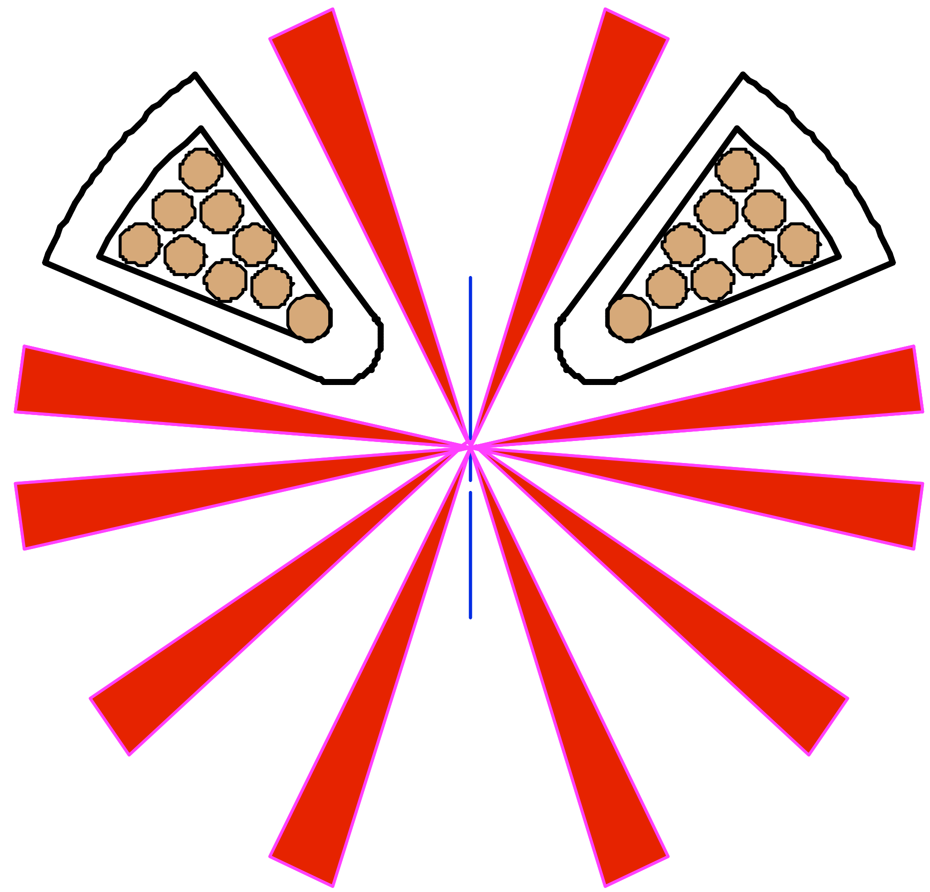
- Kapton insulated Cu wire 1mm dia, 9 turns
- The wire is encased into an enclosure
- Enclosure must be either non-conductive (epoxy? plastic? ceramic?) or have slits to eliminate the eddy currents

A similar approach can be used for other beam and diagnostic configurations

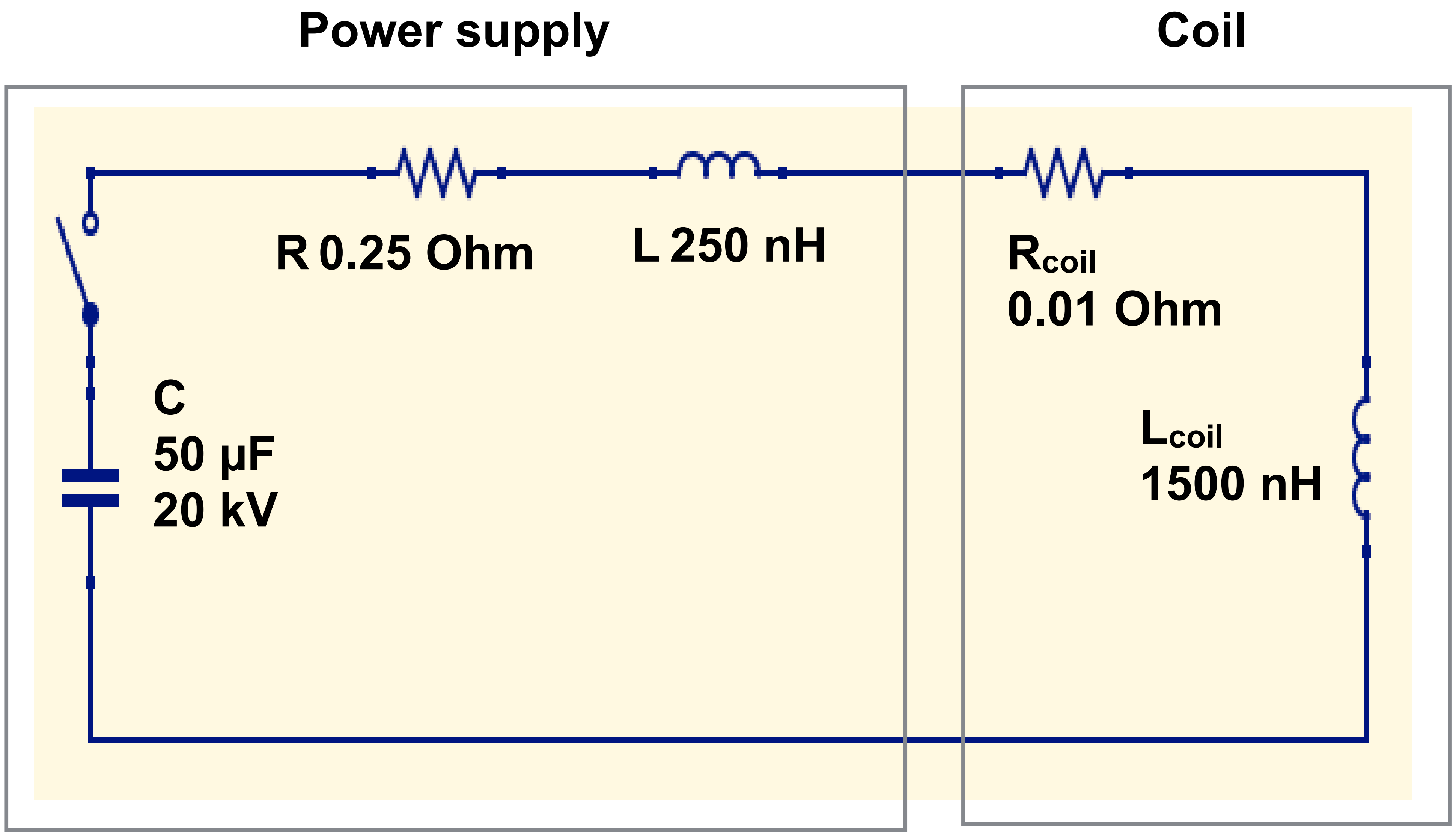
“Helmholtz” coil with equatorial access



Single coil above the equator

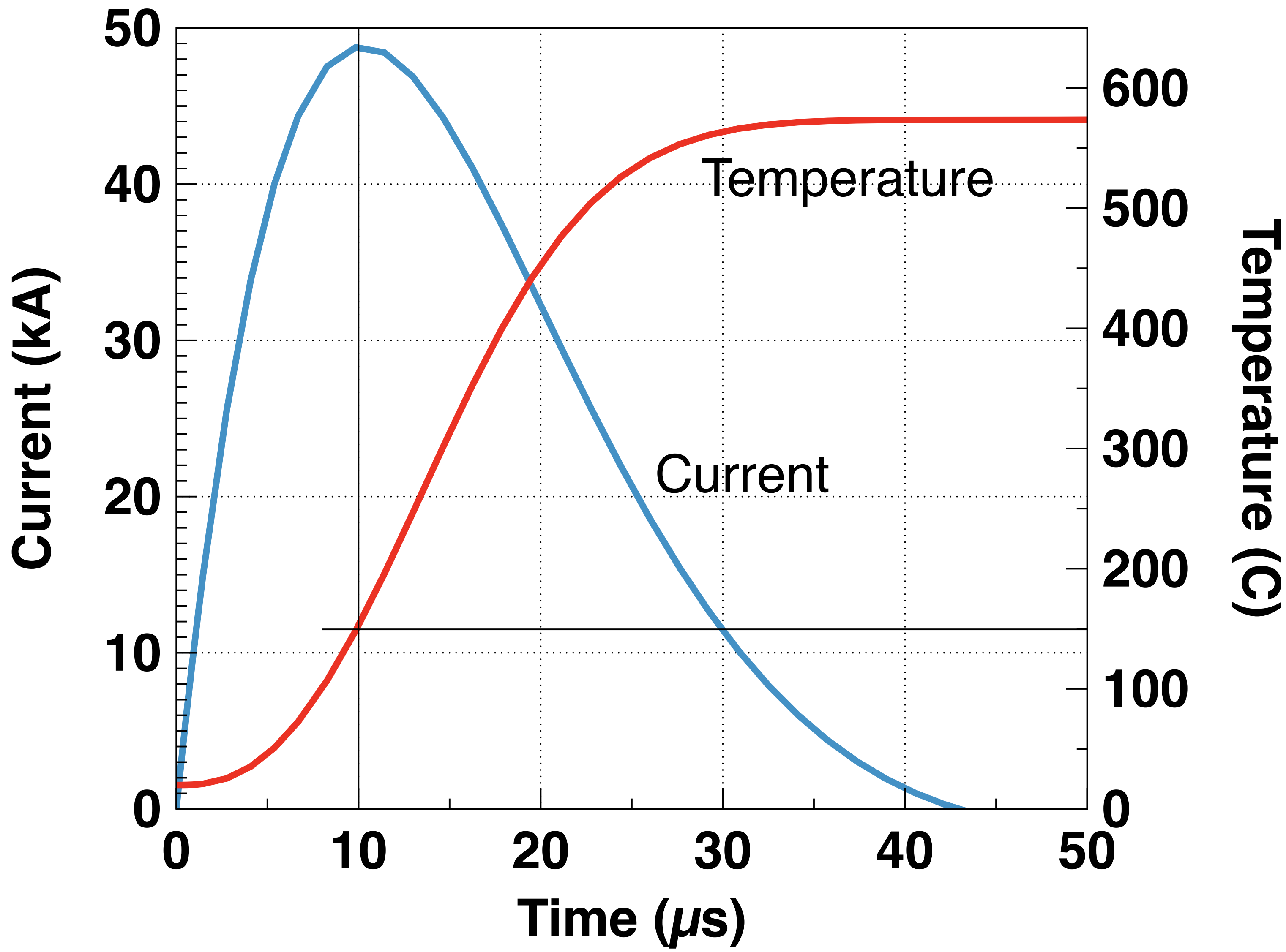


Simplified schematic of a 50 kA pulser



The coil thermal dissipation is manageable

Stored energy	10 kJ
Bfield energy	2 kJ
Coil dissipation	0.75 kJ



- At the current peak, the coil is heated up to 150 °C
- The wire stays below 50% of melting temperature for the entire pulse duration

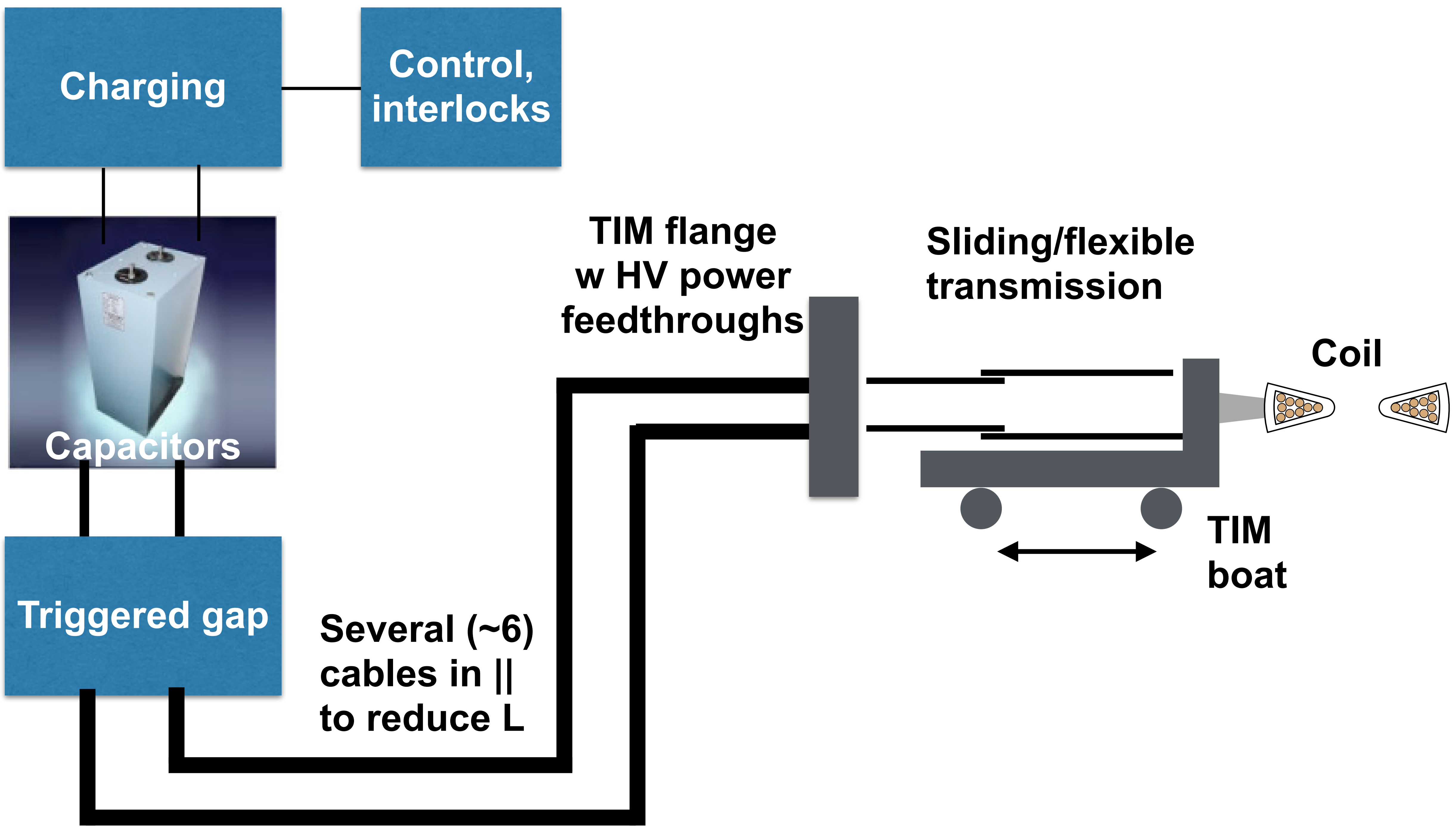
Off the shelf capacitors and switches can be used

GA 33593 - 50μF/20kV/50kA
GA 33694 - 2x 50μF/20kV/50kA

Perking-Elmer triggered spark gaps

- **Used in MIFEDS**
- **Very reliable**

Main electrical components will be outside the TIM



MIFEDS upgrade will be staged

	Stored Energy	Current/ Time to peak	Bfield	B Energy	Comments
MIFEDS 10T now	200 J	30kA/0.5μs	10 T	100 J	TIM, single pulse use
MIFEDS 30 T 1 year	10 kJ	50kA/10μs	30 T	2 kJ	Power supply outside the TIM, multi-pulse
MIFEDS 50T 2 years	25 kJ	70ka/20μs	50 T	5 kJ	Power supply outside the TIM, single-pulse

High Bfield on OMEGA is challenging (but doable)

UR LLE

- Enclosure must be either non-conductive (epoxy? plastic? ceramic?) or have slits to eliminate the eddy currents
- Coil operation options:
  - Replaceable after each shot?
  - Replaceable after each campaign?
- High voltage/High current MIFEDS interface
- Debris mitigation
- Beam and diagnostic access
- Fabrication and testing

Summary

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- Magnetized HED plasma research has greatly expanded during the last few years
- Magnetic field generator MIFEDS has become a facility diagnostic, widely used by LLE and Users
- MIFEDS flexible platform allows for wide variety of experimental configurations both on OMEGA and EP
- New and exciting results have been obtained in the areas of ICF, astrophysics-relevant applications, e-e$^+$ pair production, and others
- Work ongoing on high-B platform development - from 10T to 30T to 50T

B-field target deployment on NIF Facility Considerations

B-Field Working Group

LLNL, Oct 12-13 2015

Bruno Van Wonterghem,
Phil Datte, Mark Jackson, Dan Kalantar, Tom Kohut, Tom Parham

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXXX

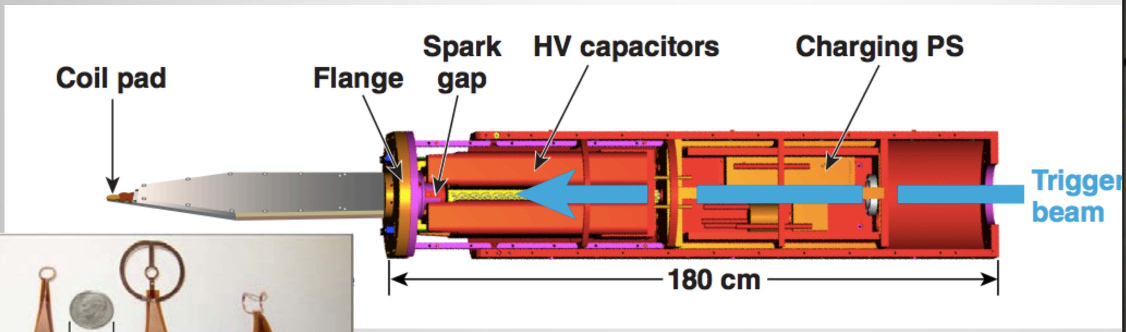
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

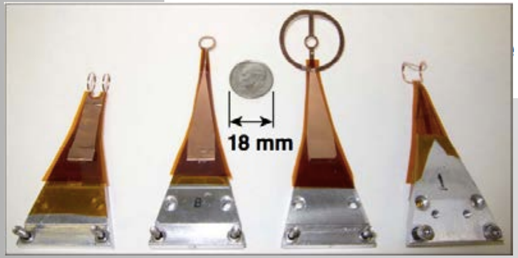
Successful implementation of B-field capability on NIF will be an iterative process

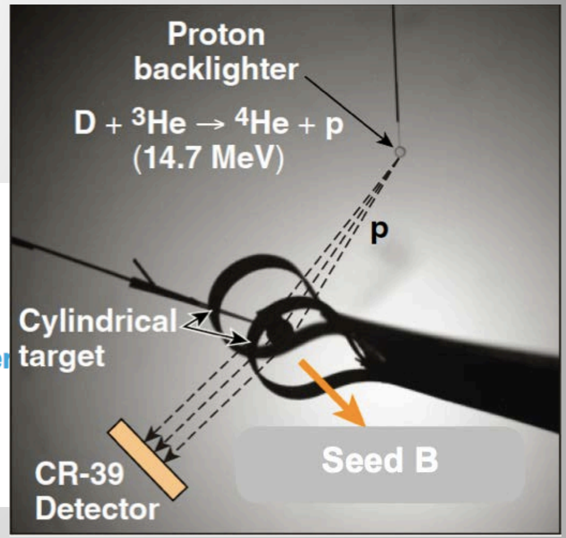
- Define requirements:
  - Detailed field strength, shape, orientation, time dependence, and uniformity requirements from the experimental design point of view
- Identify use cases:
  - Target types that require magnetic fields (warm, cryo, layered targets)
  - Diagnostic requirements (LOS)
  - Discharge or laser driven
- Develop implementation concepts:
  - Target + field coils integrated on the same positioner or separate
  - Standardization of the interfaces and implementation (common magnetizer)
- Evaluate impacts:
  - Identify facility impacts and potential mitigations
  - Implementation design
  - Lines of sight, debris & shrapnel, EMI/EMP

Examples

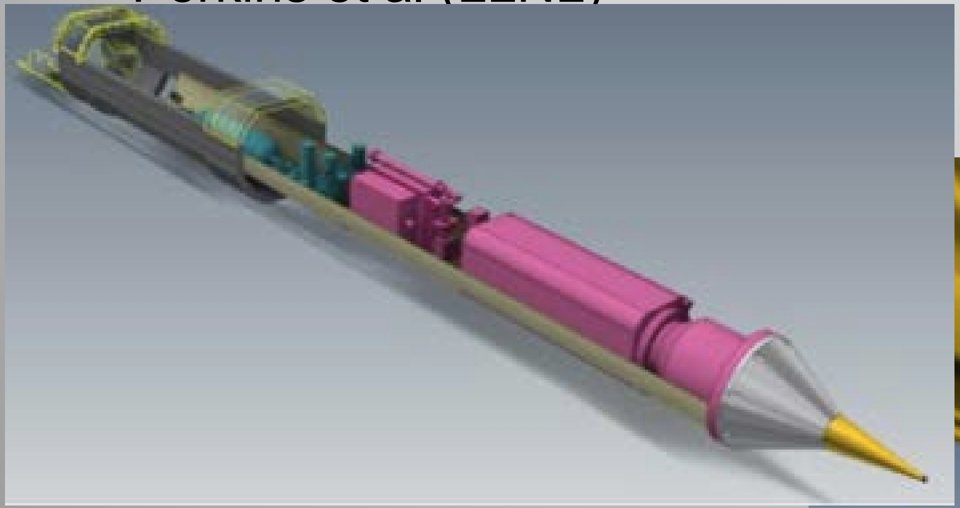
- Fiksel et al (UR LLE)

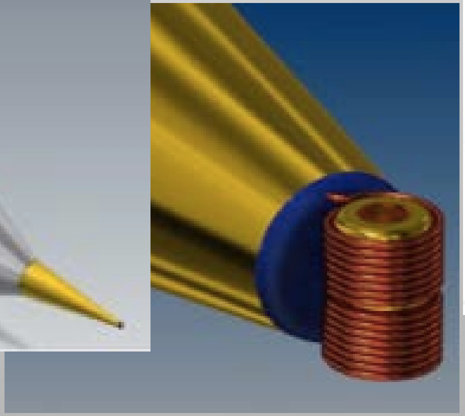


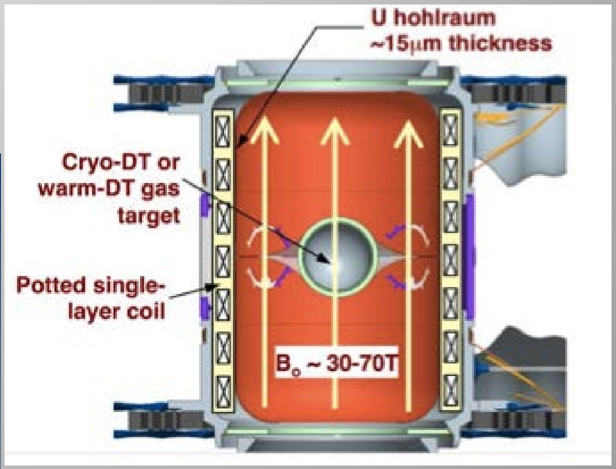




- Perkins et al (LLNL)







Facility considerations
Clearances

- Clear 3w beams
  - Maintain driver beam stayout zones

- Clear or manage unconverted light beams
  - Maintain unconverted light stayout zone or implement laser shielding in impacted area

- Clear required diagnostic lines of sight
  - Keep lines of sight open for the required diagnostic(s)

- Fit within the TAS jaws (max width and height)
  - Alignable

Facility considerations
Impacts

- Reduce additional debris and shrapnel to protect optics and diagnostics
  - Minimize coil mass (~0.5 mg), material selection
    - Testing and characterization recommended to determine debris distribution
  - Prefer designs that vaporize the coil and reduce debris
  - Conduct standard debris and shrapnel analysis, (directionality, vaporized mass, materials, energy …)

- Minimize EMI/EMP effects on TD and other equipment
  - Ensure the EMI/EMP created by the magnetic field generator and coil do not perturb the diagnostics/equipment used for the experiment in a way it affects the experimental outcome or system operation

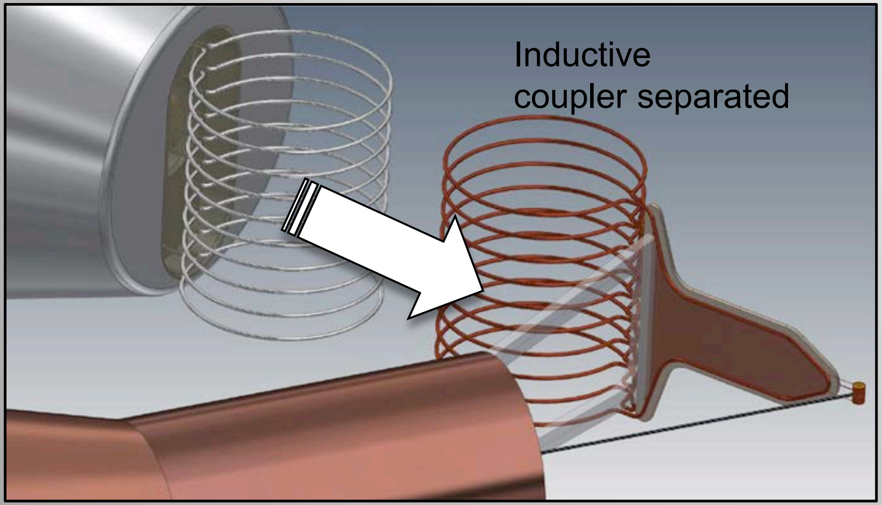
Facility considerations
Target capabilities

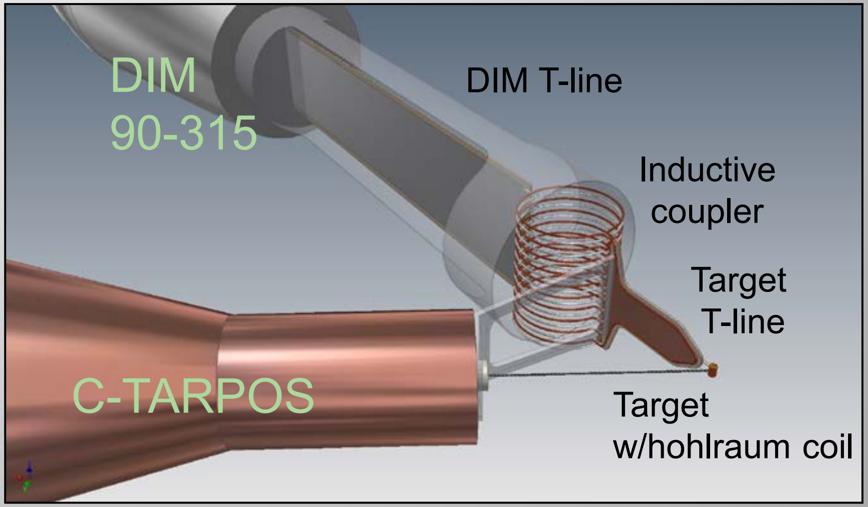
- Thermal control for CRYO targets
  - Warm or cold, temperature and accuracy (Layered?)
  - For cryo targets, are shrouds required? This will need a dedicated design effort

- Max gas release in the TC (shot time, failure)
  - The amount of gas vented into the TC during a shot shall be less than 200 standard CC

- Provide target gas fill management capability
  - What gas(ses) are needed, what pressure(s), what fill pressure tolerance
  - Tritium use drives the positioner used

Concept of CRYO Target magnetized through inductive coupling powered by DIM (Rhodes, Perkins et al, LLNL)





Target may be aligned as usual with TARPOS. Then, DIM is inserted for a no-contact power coupling. Target is not disturbed.

Facility considerations
Magnetizer implementation

- Magnetizer design compatible with positioner design and cables
  - Evaluate magnetizer pulsed power cables (what are limits)
  - Switch/trigger requirements (optical vs electrical)
  - TANDM provides dual flexible cable tray usage
  - Implementation on (CRYO)TARPOS is challenging

Facility considerations
Magnetizer implementation

- Provide stored energy containment and safety
  - Electrical stored energy and capacitor failures do need to be entirely contained inside the magnetizer enclosure with no possibility for release in the target chamber
  - Electrical safety requirements need to be met for handling/servicing in the Target Bay
  - Need a Failure Mode and Effects Analysis

- Evaluate mechanical shocks and impact on alignment
  - Evaluate timing and magnitude of mechanical shock and defromation induced by the discharge and current against alignment tolerance (alignment test stand)

Facility considerations
Interfaces

- Facility interfaces for cables/power supplies/controls
  - Location of cables and control racks
  - Local (standalone) controls or DM racks
  - ICCS controls interfaces (set up, arm, trigger)

- Rad/activation compatible design (decontamination etc)
  - Entrant magnetizer and coil systems need to be decontaminated/released (similar to snouts)
  - Evaluate activation for use in yield experiments
  - Evaluate unusual or new materials

Facility considerations
Trade-offs

- Flexibility/commonality of magnetic field generator for different targets would be highly advantageous
  - Cost effective
  - Efficient implementation and operation
  - Use coil LRU to achieve specific field parameters

- Establish requirements for offline and online characterization and calibration
  - Field strength, uniformity and gradients
  - Spatial extent and shape
  - Temporal profile
  - Field evaluation during shot and disintegration

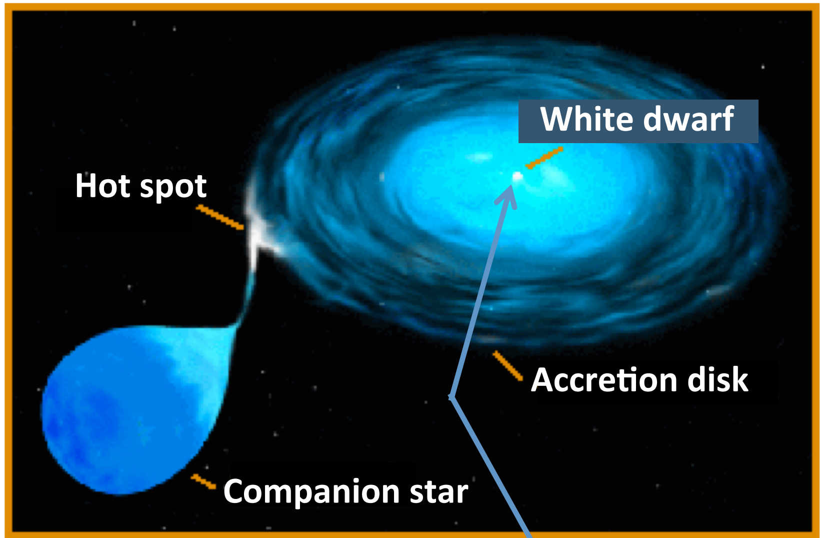
A new class of radiative MHD lab astro. experiments would be enabled by imposing pre-existing strong (> 20 T), large scale (> 1 cm^3) fields on NIF

- Example NIF experiment proposed by Michel Koenig and Emeric Falize et al. (Ecole Polytechnique)
- Aspects of the dominant radiative-MHD microphysics of magnetic cataclysmic variables (accreting magnetic white dwarfs or "Polars") could be studied on NIF
- LULI results showed such scaled experiments should be possible on NIF

[E. Falize et al., HEDP 8, 1 (2012)]

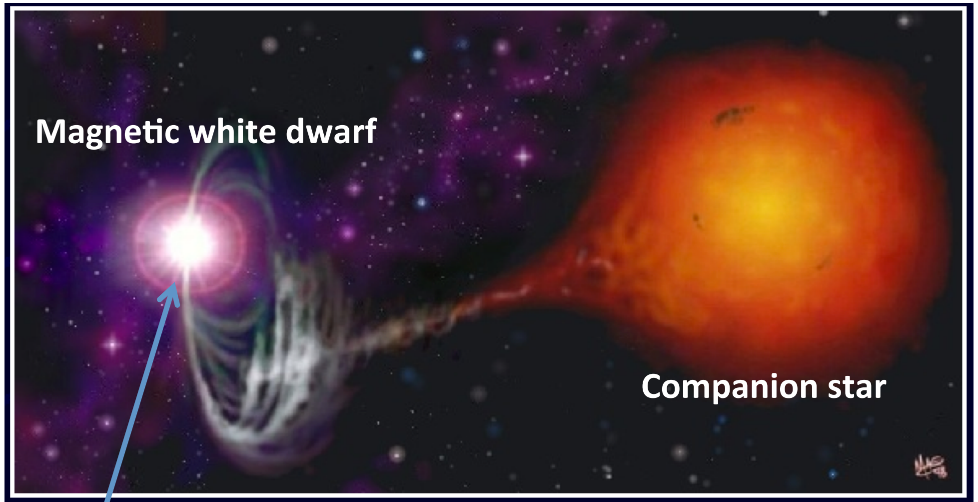
Fluid param	magCV shock	LULI exprmt
h_s(cm)	10^7	5×10^{-2}
t(s)	1	5.5×10^{-8}
v_a(km/s)	1000	80
ρ_a(g/cm^3)	10^{-8}	10^{-2}
T_{ps}(eV)	10^4	15
M	>10	3
χ_{ps}	<<1	1
Bo_{ps}	>>1	15
R_{ps}	>>1	2×10^4

Cataclysmic variable (CV)



Non-magnetic, accreting white dwarf

Magnetic CV or "Polar" or AM Herculis stars



Accreting magnetic white dwarf:
matter collimated to the magnetic poles

Experiment: Radiation hydrodynamic accretion processes in X-ray binary stars

Experiment: *Koenig/Falize/ Albertazzi, and team (Ecole Polytechnique)*

NIF shots from: Discovery Science

Team: *Foster(AWE), Busschaert(CEA), Casner (CEA), Bonnet-Bidaud (CEA), Drake (Michigan), Kuranz (Michigan), Gregori (Oxford), Liberatore (CEA), Graham (AWE), Sakawa (ILE), Mouchet (LUTh), Ciardi (LERMA)*

Important aspects of the experiment:

- **Key B-field requirements :** 30 T or more, uniform over several mm^3
- **Approximate schedule:** ~fy18
- **Experiment can be done in a phased approach – with phased increases in B strength:** A NIF proposal with a tube for collimation is under review for DS fy17-18

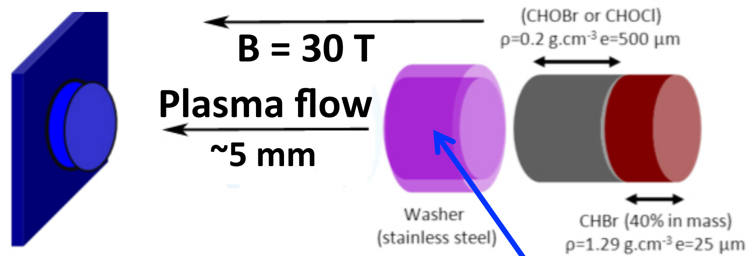
Experimental objectives: Obtain density and temperature experimental data to resolve a long standing debate on accretion column models regarding the coupling between radiative flows and magnetic fields

Key physics related to the B-field: collimation of an accretion column with the B field

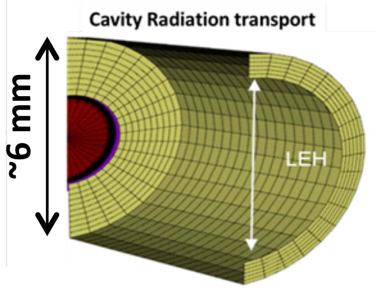
Expected results: collimation should increase the strength of reverse radiative shock making it radiative

Ta obstacle

Experimental configuration



NIF "scale-1" halfraum



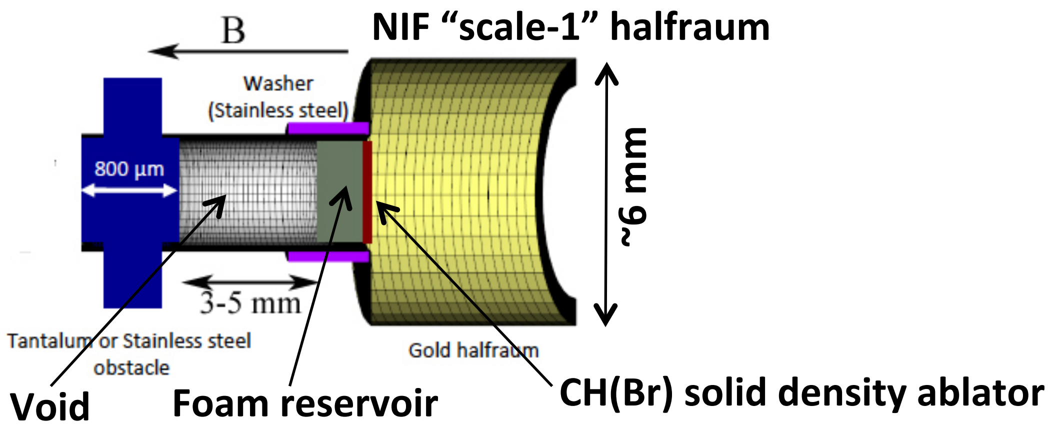
Require B field of ~30 T, ~1 cm^3 for collimation, causing stronger reverse shock that becomes radiative, similar to magnetic cataclysmic var.

Void (gap) inside the washer, across which the shock-releasing plasma flow travels until it stagnates on the Ta obstacle

Requirement: **B-field spatial extent**

This experiment requires a magnetized volume ~1 cm^3

Considering the distance between main solid target and the obstacle on the halfraum, we expect a total volume lower than 1 cm^3 to be magnetized (≈ 4 times smaller at maximum stagnation shock strength)



In the central region, where the plasma flow propagates, we need a quite uniform field to avoid strong B-field gradients (require gradient <~0.5 T/mm).

To achieve this goal, it would be best to have:

- *A capacitor bank of ~ 24 kV, ~ 1MJ with 16 capacitors of ~ 250 µF each*
- *Crowbar resistors*
- *Inductive current limiters to avoid damping of the current pulse which produce additional forces in the split-coil.*

This experiment requires a B≥ 20 T and uniformity to 10%

B-field magnitude :

- the B field must be over 20 up to 40 T (more if possible)

B-field spatial variation requirements

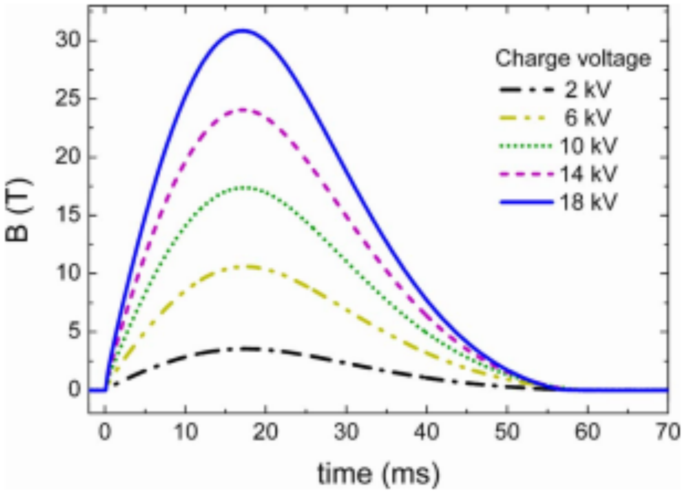
- The B field must be uniform on about 1 cm^3 with a gradient ≈ 0.5 T/mm at maximum.

B-field spatial uniformity requirements

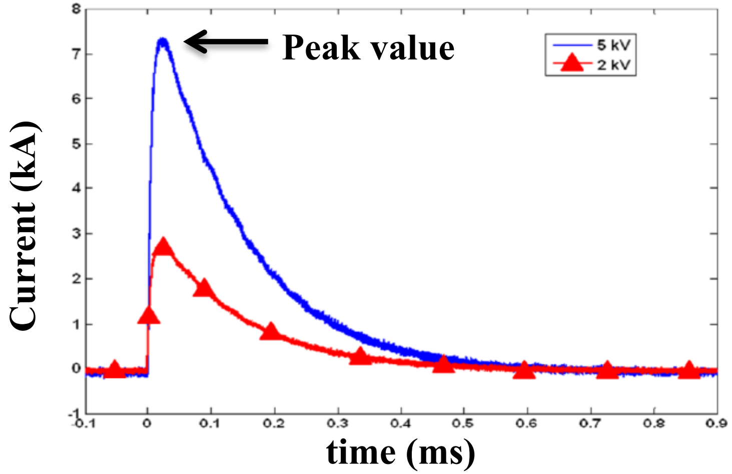
We should have a small B-field gradient in the center of the coil of the order of 0.5 T/mm in longitudinal and radial direction.

This experiment requires a ~2 μs interval of constant B

Typical rise-time using a 1 MJ capacitor bank for a 31 T B-field



Typical rise-time using a 32 kJ capacitor bank for a ~ 10 T B-field



The rise-time is strongly dependent on the capacitor bank. For a 32 kJ and a 20 T B-field constant over ~ 2 μs (98% of the peak value) the rise-time should be of ~10-200 μs.

For a 1 MJ, the rise time should be of ~ 10-20 ms maximum.

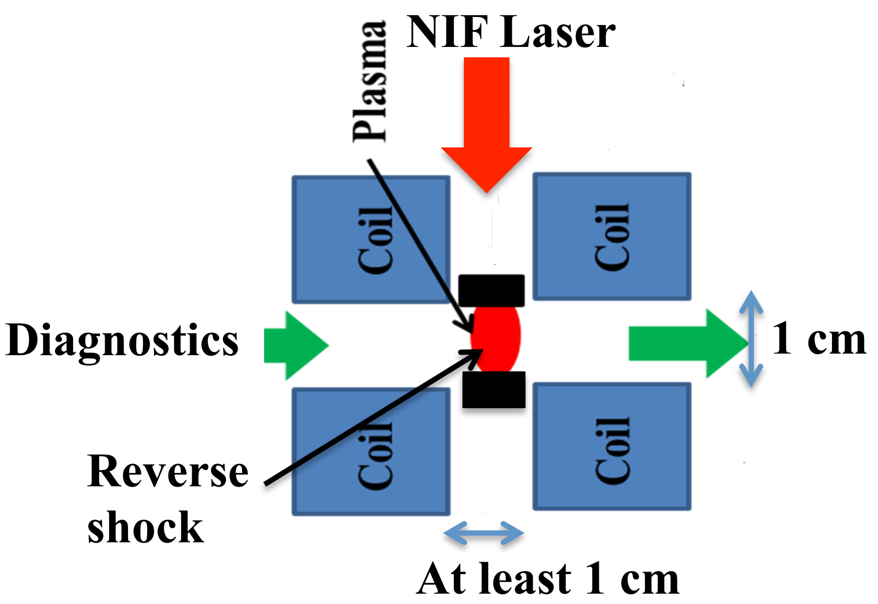
The rise time is not a major issue BUT the peak current should be constant over 2 μs at least (> 98% of the peak value)

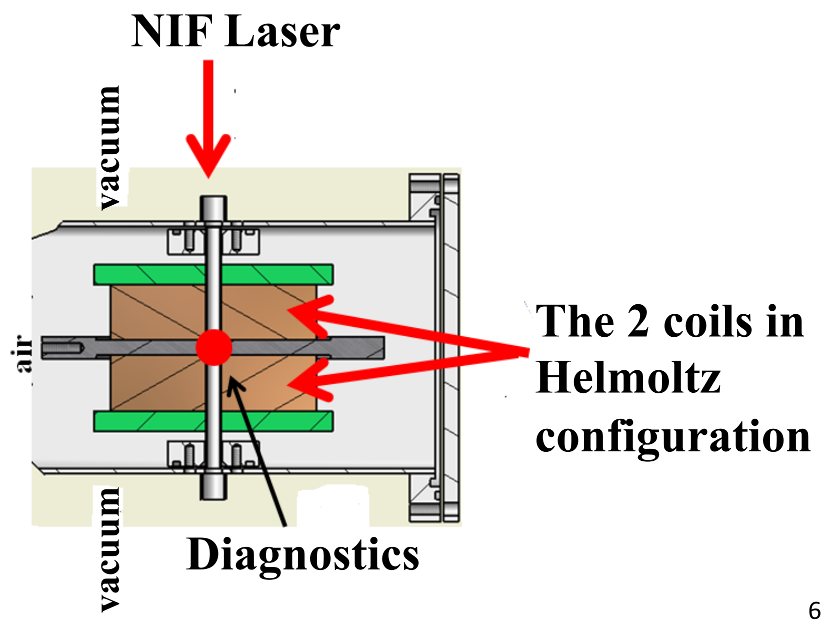
Requirement: Diagnostic access

This experiment requires diagnostic access for these measurements…

How to diagnose this experiment

- Use **DANTE** to get the Tr(t)
- Use **x-ray backlighting** to probe the flow and reverse shock variables
- Use **x-ray backlighting** to perform x-ray spectroscopy to determine the temperature in the reverse shock



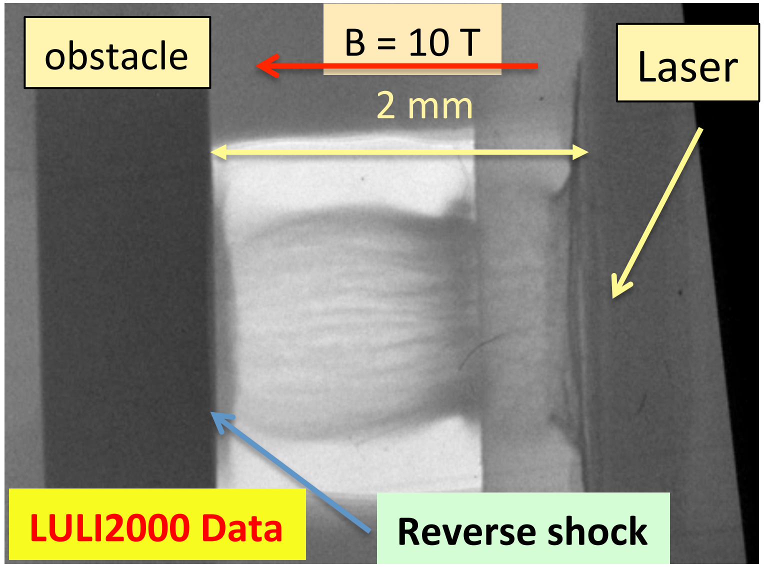


Experiment: Radiation hydrodynamic accretion processes in X-ray binary stars

This experiment is following the proposal P-000050 POLAR experiment (PI: Falize)

- The radiation transport platform (RTp) will be used to drive a strong shock through a low density foam to generate a high velocity supersonic plasma flow on release that will impact and stagnate on a solid obstacle mimicking a white dwarf atmosphere
- The RTp will produce a sufficiently long x-ray pulse to drive the large material mass contained in a reservoir, producing high flow velocities: conditions similar to astrophysical conditions can be achieved
- The B-field must be parallel to the flow propagation in order to collimate it and prevent lateral decompression, strengthening the radiative stagnation shock.

- The key diagnostics in this experiment will be the x-ray framing radiograph diagnostic with the 6x hGXD (2 strips) inserted in DIM (90,78). Two Dante are required to infer the raditiave temperature from the halfraums
- As we remove in this experiment the original tube to collimate the plasma flow, access to emission from the flow or reverse shock will allow the use of x-ray spectrometry



Bring up any other issues

The capacitor bank should be protected from failure in case of a short circuit in one capacitor.

We need inductive current limiters to avoid forces in the coil that could induce easier failure.

Coil under air should be better to protect optics inside the chamber

No metals inside the coil if rise-time is long (> ms)

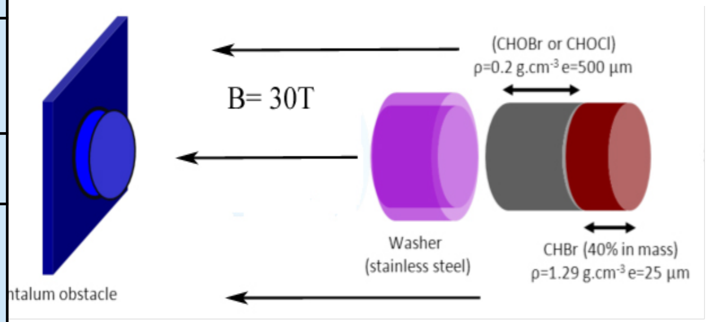
Summary

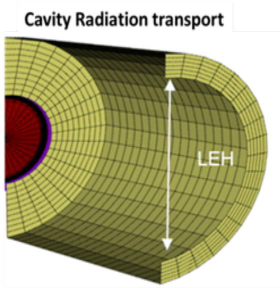
Experiment: Radiation hydrodynamic accretion processes in X-ray binary stars

Summary requirements

B-field magnitude	10 - 30 T
B-field spatial shape / extent	1 cm^3; uniform field shape
B-field uniformity	10% over the required volume
B-field rise time	2 µs
Diagnostic access	X-ray radiography and spectroscopy at several positions
Other	None

Summary experiment sketch

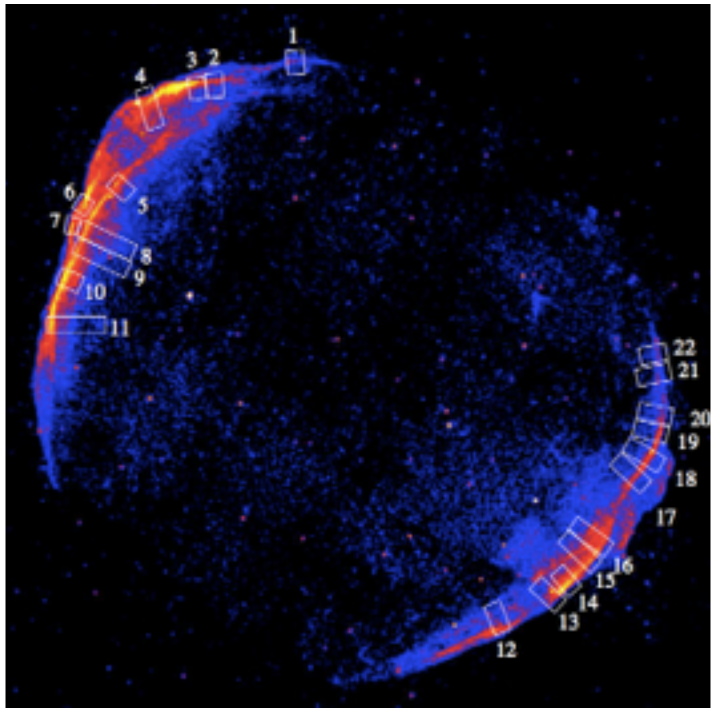




B needs to cover ~3 mm diam. x ~5 mm cylindrical volume

Exploring the Physics of Magnetized Shocks on NIF

Frederico Fiúza (SLAC)
Anatoly Spitkovsky (Princeton)



SLAC NATIONAL ACCELERATOR LABORATORY
PRINCETON UNIVERSITY
Lawrence Livermore National Laboratory
UNIVERSITY OF OXFORD
Stanford
@MIT PSFC
THE UNIVERSITY OF CHICAGO
UR LLE
UNIVERSITY OF MICHIGAN
FAU

We propose to study in the laboratory the physics of magnetized shocks of relevance to particle acceleration in astrophysics

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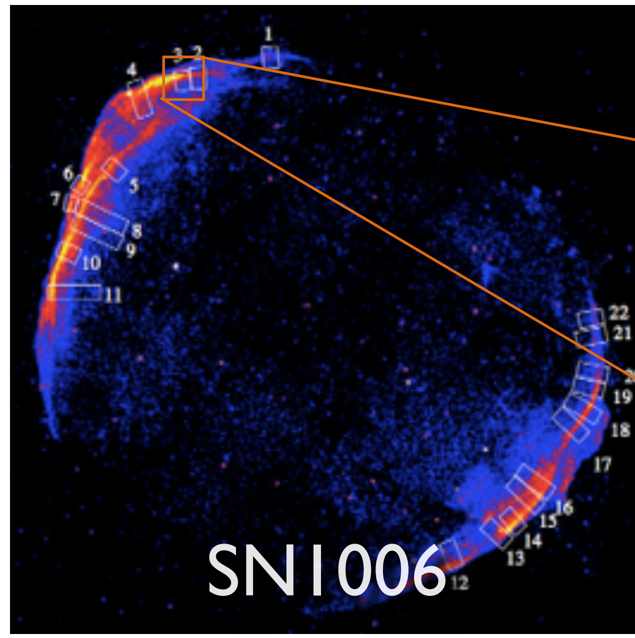
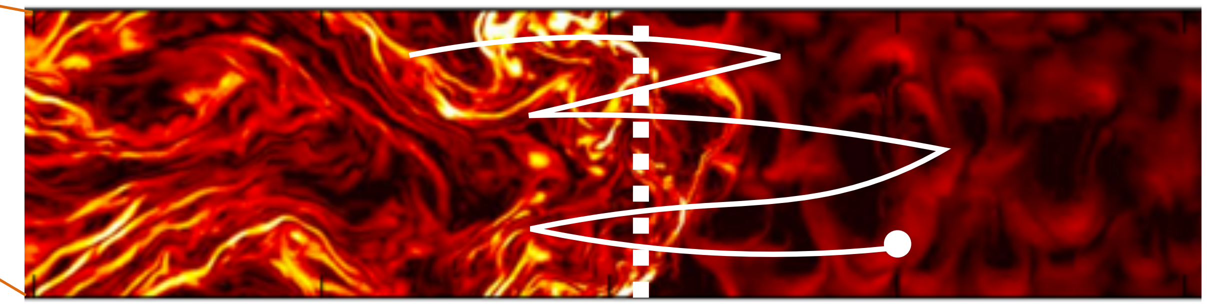


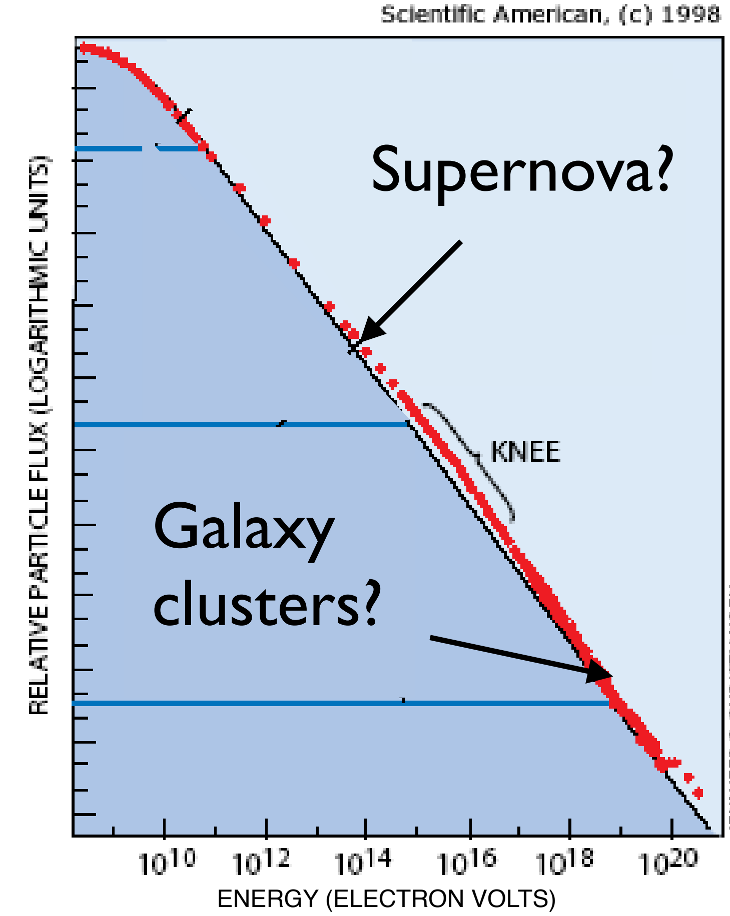
Particles are Fermi accelerated



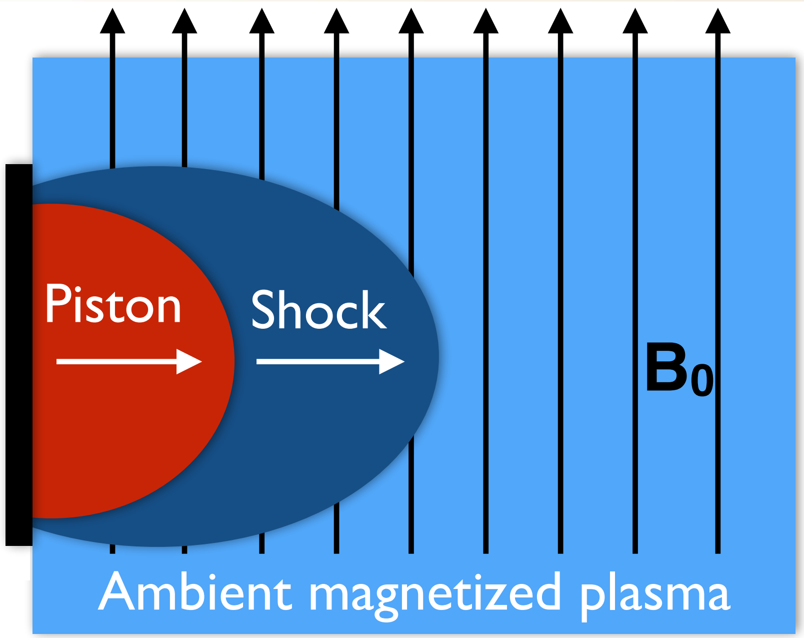
shock front

- Collisionless shocks are ubiquitous in astrophysical environments and believed to be responsible for acceleration of cosmic rays
- Majority of collisionless shocks of interest are magnetized with $v_{shock} \sim 1000$ km/s and $M_A = v_{shock}/v_A = 7\text{-}100$
- How the physics of shock formation and its associated field structure depend on the plasma conditions is not yet well understood
- Information from astronomical observations is limited and numerical simulations are not yet able to capture the physics of magnetized shocks from first principles

Scientific American, (c) 1998



Only NIF allows the generation of large enough collisionless plasma volumes to have impact in plasma astrophysics



> 10 T nearly uniform B-field in cm^3 volume is needed in order to probe the physics of colliisonless magnetized shocks

We aim to use the NIF laser beams to drive a high-velocity (1000 km/s), high-M_A (> 7), large scale (>> ion Larmor radius) piston into an ambient collisionless magnetized plasma to:

- Demonstrate the generation of high M_A magnetized collisionless shocks for the first time in the laboratory
- Characterize the shock structure (v, n, Te, Ti, E & B fields) for different M_A and compare with observations (Te/Ti is obtained from Balmer lines)
- Characterize the E,B field structure ahead of shock to determine the dominant wave generation and particle injection mechanisms

The measurement of Te/Ti and the field structure at the shock and upstream regions on NIF will dramatically expand our understanding of particle injection in magnetized shocks and impact theoretical, experimental, and observational programs

Our main diagnostics are proton radiography and Thomson scattering

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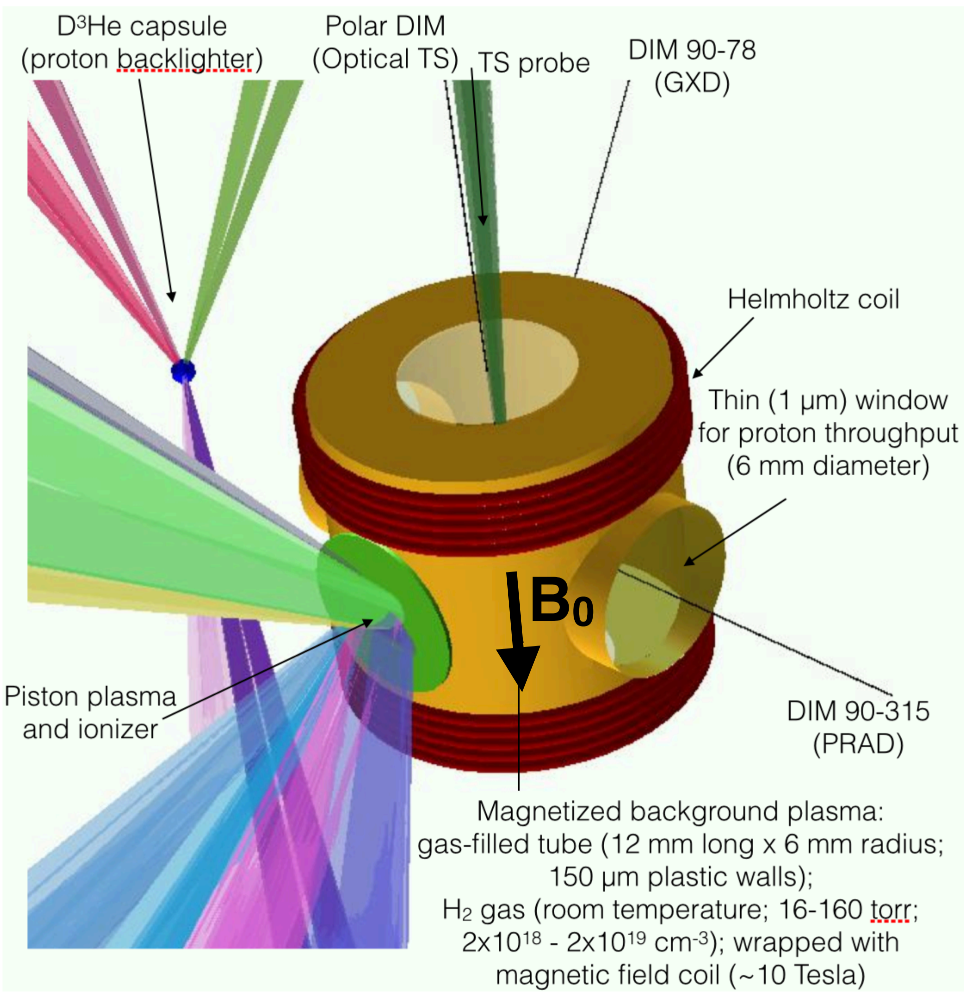
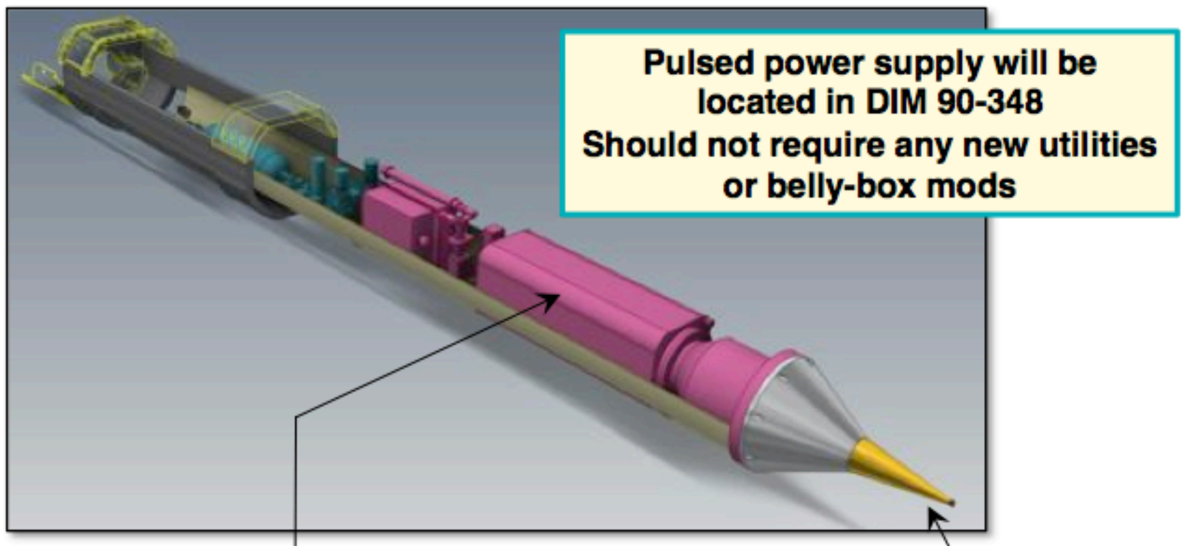
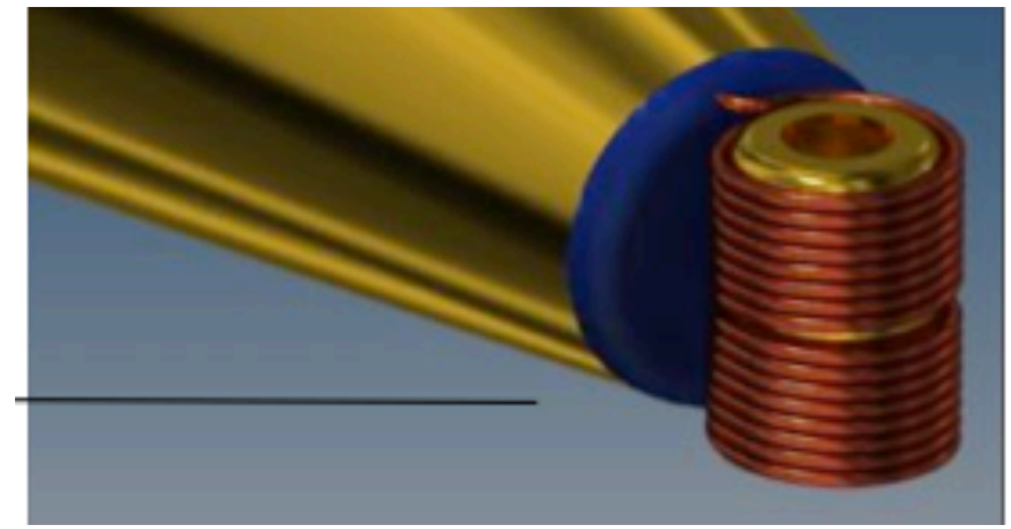


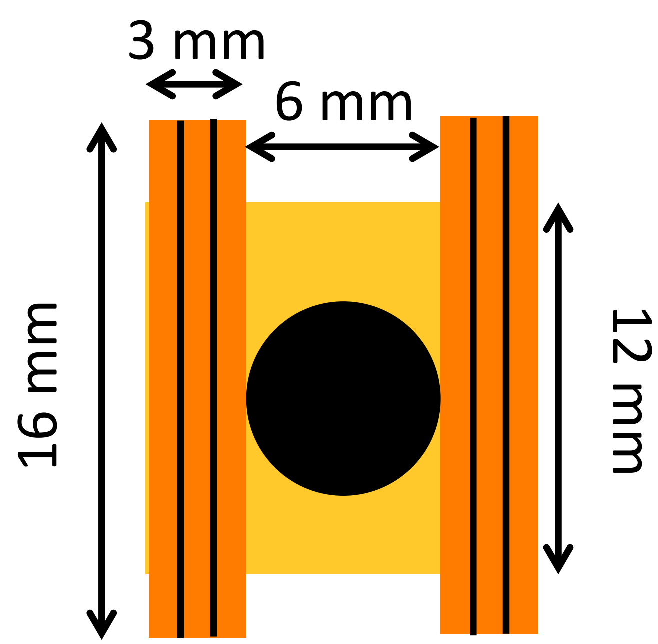
Diagnostics	Location	Priority	Measurements
Proton radiography (Prad) - CR39	90-315 0-0	1	Shock E and B field imaging from 2 angles
OTS	0-0	1	Plasma conditions (v, n, T)
NTOFs		2	Neutron yield from D^{3}He
SXI, U/L	Fixed	2	Time-integrated piston imaging
Dante 1	143-274	2	X-ray yield
FABS	31B	2	Backscatter, time-resolved polarimeter for B-field measurements
NBI	31B	2	Backscatter
pTOF, WRF, SRF, GXD	90-78	2	protons from D^{3}He

D^{3}He backlighter produces 3 MeV and 14.7 MeV monoenergetic protons, allowing us to study relative strength and structure of E and B fields (deflection angle has different energy dependence for E and B)

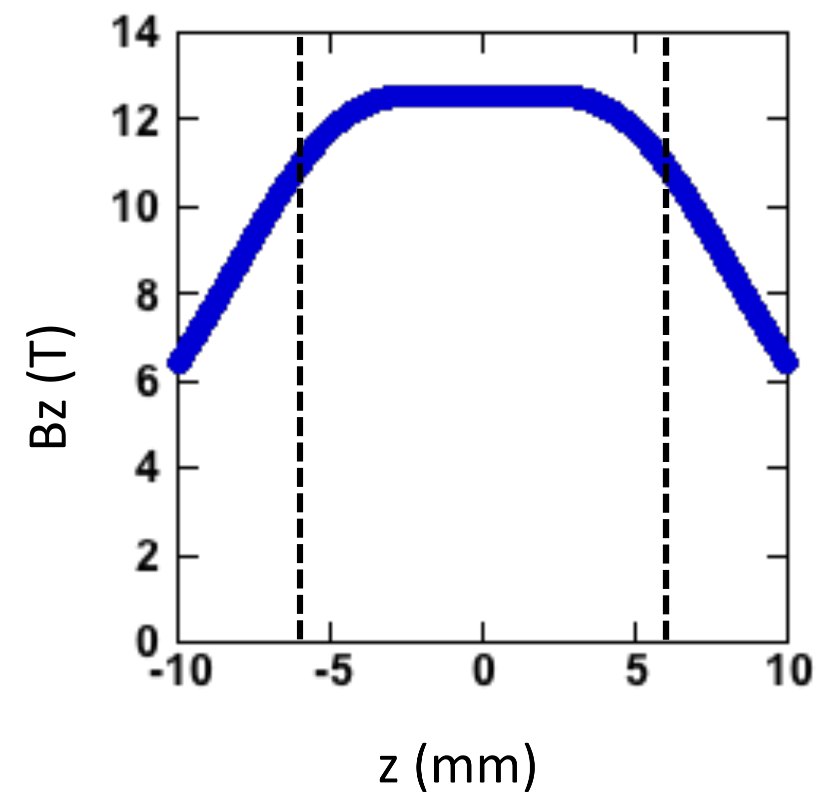
We need > 10 T Helmholtz B-field in cm^3 volume







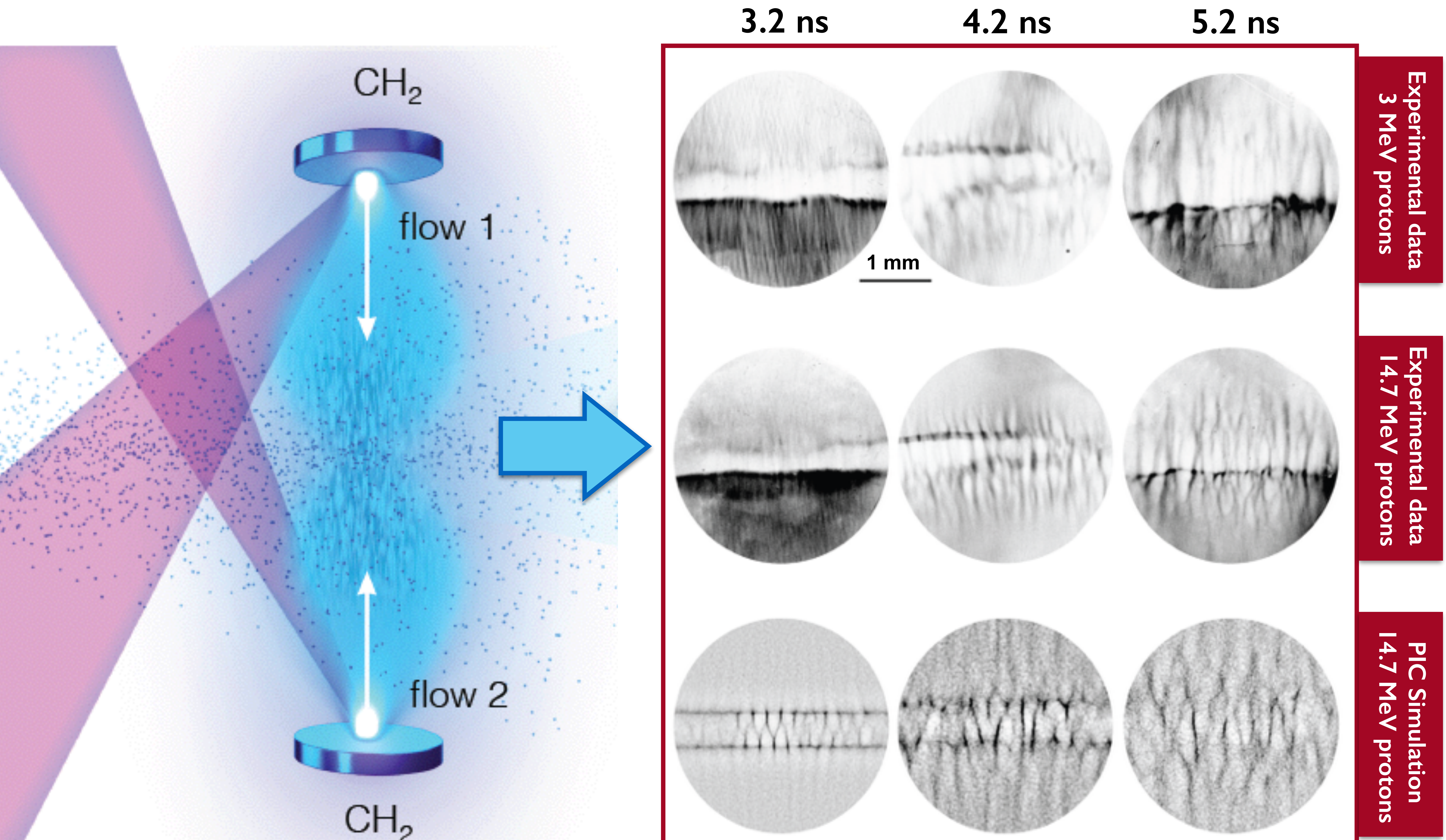
3 turns each side, 40 kA



B-field capability is currently being designed for a maximum current of 80 kA, but 40 kA would be enough for our experiments, producing 12 Tesla (or ~ 10 T cm^3)

courtesy of J. Perkins and M. Rhodes

We have been highly successful at probing B-field structures with D^3He proton radiography and comparing the results with 3D PIC simulations at OMEGA

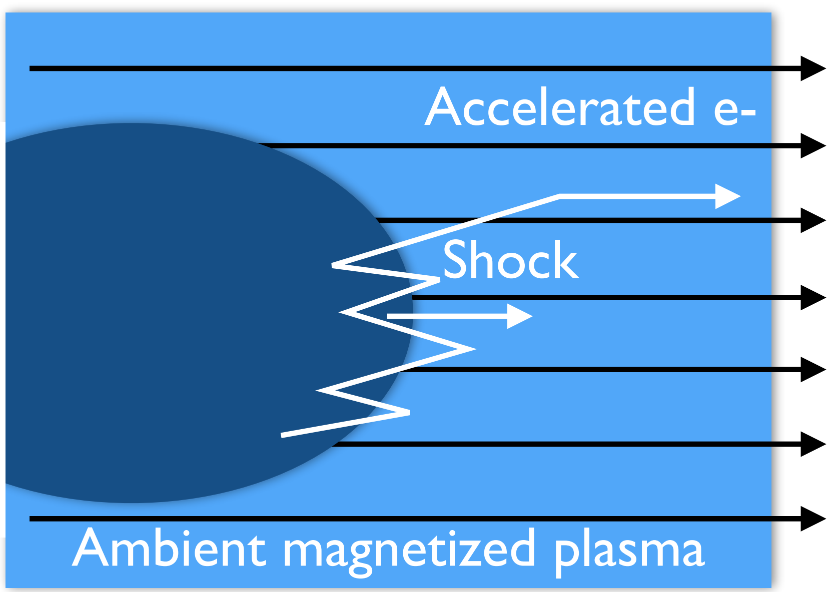


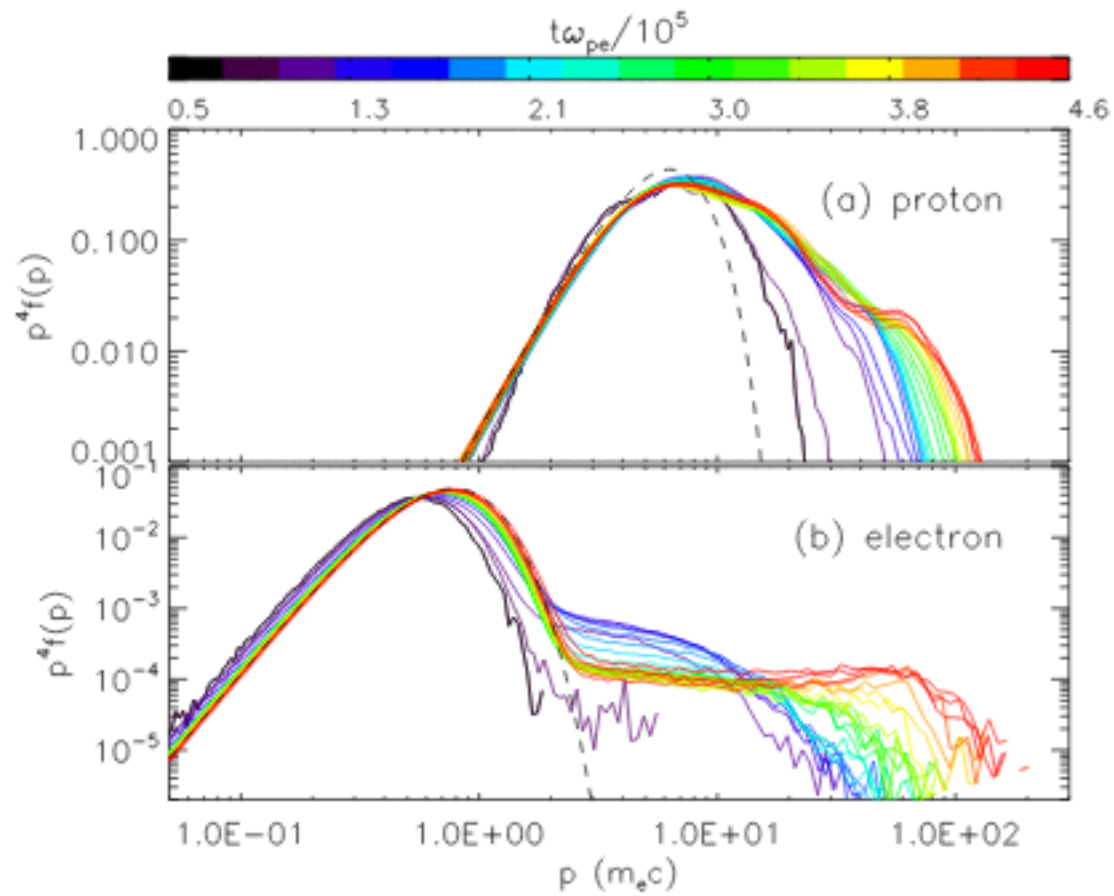
Proton deflection at 3 MeV vs. 14.7 MeV indicates magnetic fields

C. Huntington, F. Fiuza, J. S. Ross, *et al.* Nature Physics (2015)

With higher B-field volume we could access Fermi acceleration in shocks

e.g. parallel shock





- To observe strong e- acceleration (~100x k_B Te) shock needs to propagate for > 10-20 Ω_{ci}^{-1}, which for our conditions corresponds to ~ 20 ns (2 cm)
- Accelerated electrons escape along field lines allowing measurement of power-law spectrum extending to up to ~ MeV energy
- This would require a 10 T field in ~ 6 cm^3

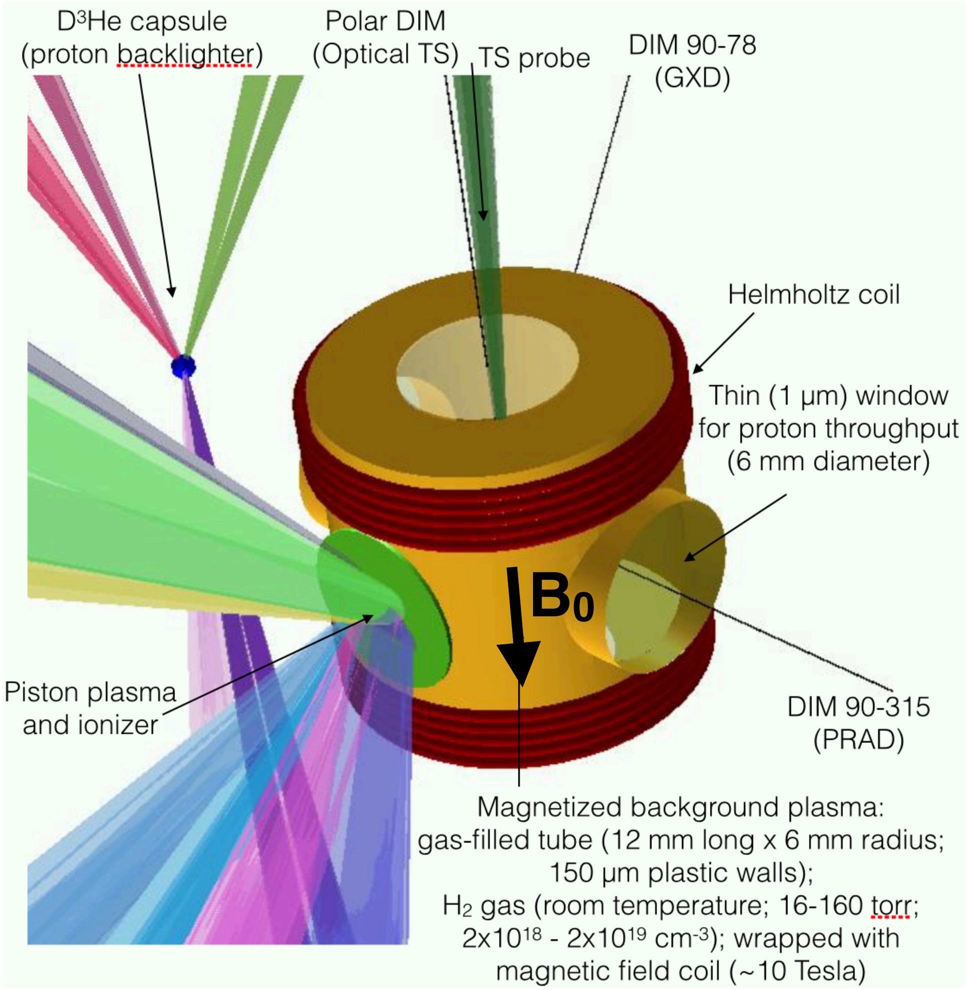
J. Park, D. Caprioly, A. Sptikovsky, PRL 2015

Conclusions

- Laser-driven HED plasmas offer a unique opportunity to study the physics of magnetized shocks of relevance to astrophysics
- NIF laser energy is required to drive a fully formed magnetized collisionless shock: high-velocity (>1000 km/s), high-MA (> 7), large scale (>> ion Larmor radius)
- A 10 Tesla, nearly uniform B-field in cm^3 volume is needed to drive and probe the shock
- Shock field structure can be probed with proton radiography proving critical insight for theories of particle injection in astrophysical shocks
- By increasing the volume to 60 T cm^3 we could probe for the first time Fermi acceleration in the laboratory

Conclusions

B-field magnitude	10 - 40 T
B-field spatial shape / extent	1 - 6 cm^3
B-field uniformity	25% over the required
B-field rise time	~ μs
Diagnostics access	Proton radiography, Thomson scattering,



We have put together a strong international collaboration to carry this effort

SLAC

Names	Affiliations	Role / Responsibilities
F. Fiuza A. Spitkovsky	SLAC Princeton	PIs, lead in design, scientific input, and PIC simulations
H.-S. Park, S. Ross, B. Pollock	LLNL	Lead experimentalists, experimental data analysis, coordination between team and NIF
G. Gregori D. Froula	Oxford LLE	Thomson scattering measurements and data analysis
R. Petrasso C. K. Li	MIT	D^3He proton backlighter measurements
D. Ryutov P. Drake	LLNL Michigan	Scientific and theoretical support
D. Lamb, P. Tzeferacos S. Wilks	Chicago LLNL	Rad-hydrodynamics and Rad-MHD simulations
W. Dawson S. Funk T. Abel	LLNL/UC Davis FAU Stanford	Connection to observational data and astrophysical context

2 page Physics summary (1)

Experiment: Fermi acceleration at shocks

Experiment: Fermi acceleration
Responsible Org: TBD
NIF shots from: DS
Shot RI: H. –S. Park / G. Gregori
Engineer: TBD

Experimental objectives: Demonstrate that 1st order Fermi acceleration can occur in converging flows. First experimental verification of a process believed to occur at supernova remnant shocks.

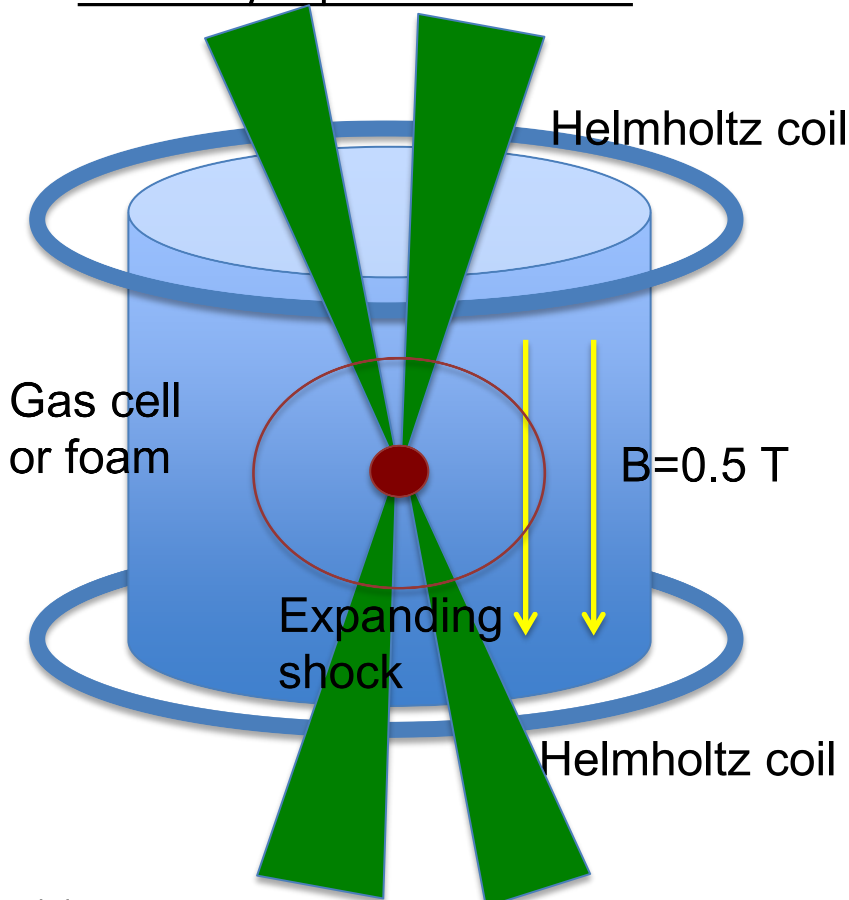
Key physics related to having a B-field: Plasma needs to be pre-magnetized. Shocks expanding in magnetized plasma.

Expected results: Measure electron spectrum and proton spectrum

Important aspects of the experiment:

- **Need 0.5 T over >1,200 cm³ volume (12 cm dia x 12 cm long tube)**

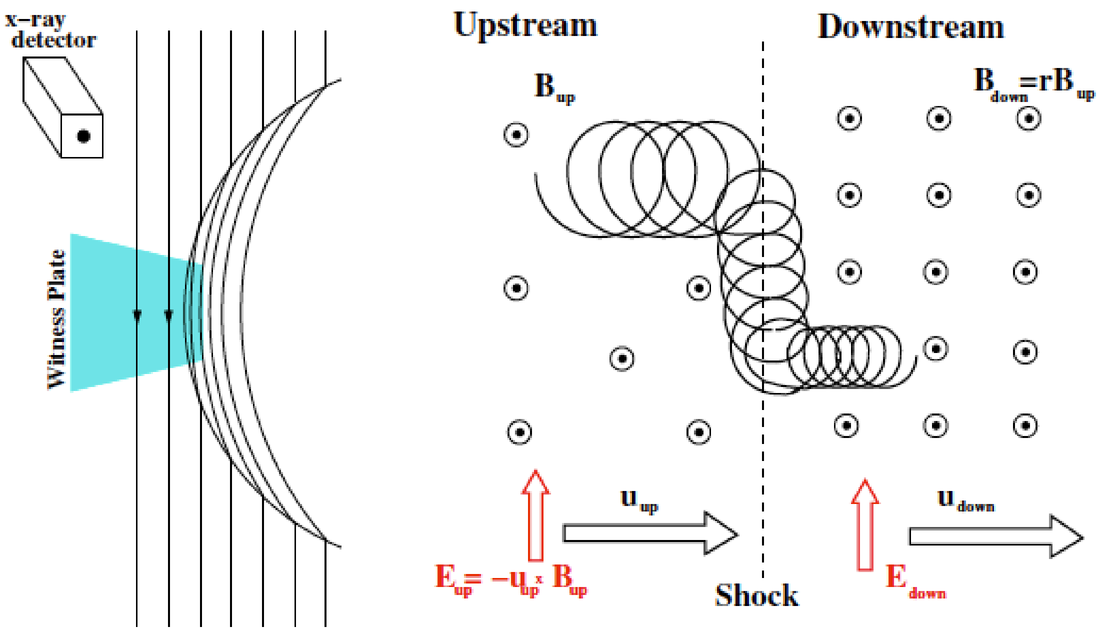
Summary experiment sketch



2 page Physics summary (2)

Experiment: Fermi acceleration at shocks

- Shock acceleration has been a key interest to astrophysics community
- Expanding shock becomes Sedov-Taylor
- Acceleration expected when radius of shock > 2 cm and electron max energy ~1 keV (Reville et al. New J. Phys. 2013)

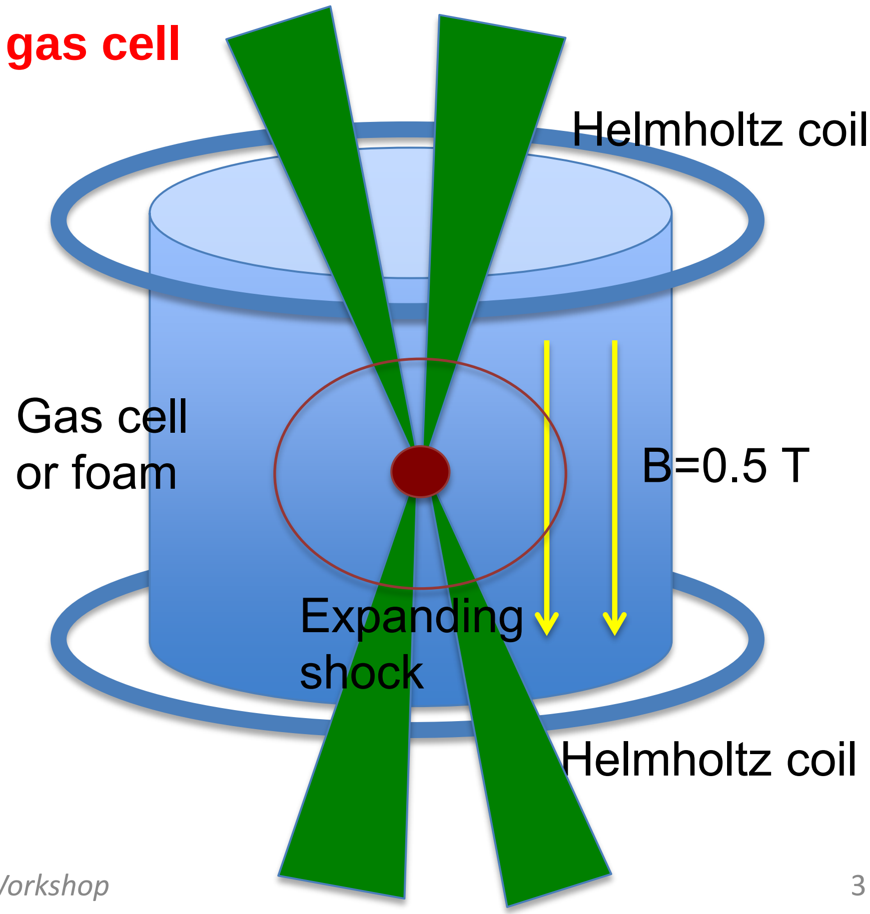


2 page Physics summary (2)

Experiment: Fermi acceleration at shocks

More detailed experimental sketch showing:

- **Large gas cell: 12 cm diameter, 12 cm long**
- **Hydrogen gas fill (n_e~10^{16} cm^{-3}), alternatively, foam filled plastic hohlraum would work**
- **CD capsule placed in the center of the gas cell**
- **NIF beams (400 kJ) used to illuminate capsule and drive shock in the ambient gas/foam**
- **Expanding shock becomes Sedov-Taylor**
- **Acceleration expected when radius of shock > 2 cm and electron max energy ~1 keV (Reville et al. New J. Phys. 2013)**



Requirement: **B-field magnitude**

This experiment requires a B≥ 0.5 T and uniformity to better than 25%

B-field magnitude ~ 0.5 T

B-field spatial variation requirements: Helmholtz field, or whatever gives more uniform field distribution

B-field spatial uniformity requirements: as uniform as possible

This experiment requires a magnetized volume of 1,200 cm^3

Approximate magnetized volume: 1,200 cm^3

Spatial shape of magnetized region: cylinder, 12 cm diameter, 12 cm long

Proposed source current path for achieving this: total magnetic energy in the volume ~80 J

Requirement: **B-field rise-time**

This experiment requires the field to turn on no faster than 2 μs

No special rise time requirements

Requirement: Diagnostic access

This experiment requires diagnostic access for x-ray imaging/spectroscopy and particle spectroscopy

Neutron ToF

Proton spectrometer (magPTOF)

Proton self-emission imaging

Time resolved electron spectrometer along the cylinder axis

Gated transverse x-ray imaging

Gated transverse x-ray spectroscopy

Bring up any other issues

One slide:

Machine safety considerations (debris, laser damage, backscatter, diagnostic damage risk, etc)

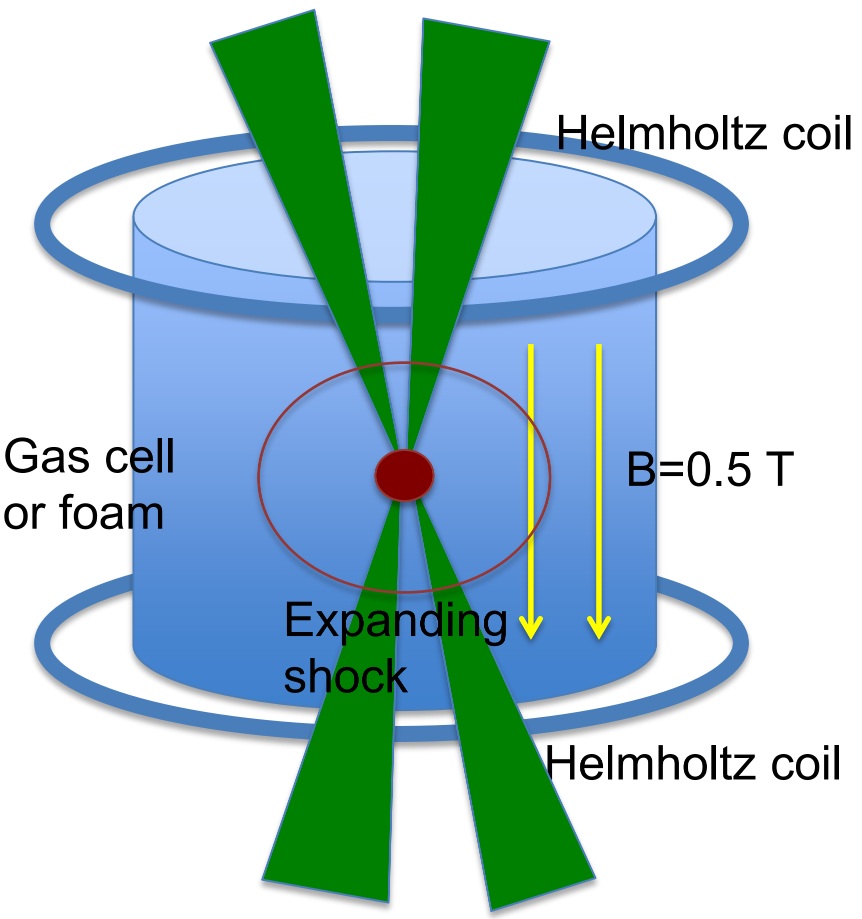
Feel free to share insights on working out solutions to any of these issues

- Debris mitigation of large volume detector (albeit low mass)
- Construction and debris mitigation of a large volume B-field coil
- Proper backscatter calculation or PQ experiment for gas or foam field hohlraums

Summary

Experiment: Fermi acceleration at shocks

Summary experiment sketch



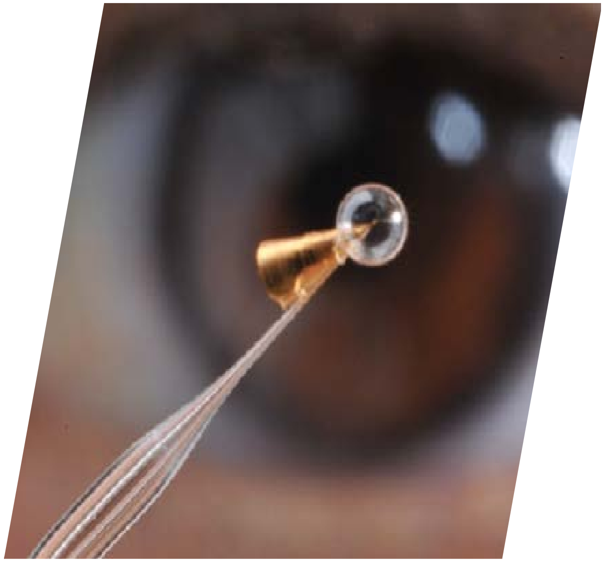
Summary requirements

B-field magnitude	**0.5 T**
B-field spatial shape / extent	**1,200 cm^3; Helmoltz coil**
B-field uniformity	**25% over the required volume**
B-field rise time	**2 μs**
Diagnostic access	**X-ray spectroscopy,/imaging, particle spectroscopy/imaging**
Other	**None**

This is complementary proposal to collisionless shock experiment

Generation of Kilo-Tesla B-field for Laser Fusion & Laboratory Astrophysics





Shinsuke Fujioka*
*Institute of Laser Engineering, Osaka University, Japan

Japan-US Symposium on Giant Laser Physics

SUMMARY

Generation of kilo-tesla B-field

- ✓ Kilo-Tesla B-field is generated with the laser-driven capacitor-coil scheme.
- ✓ Strength (600 – 700 T) of B-field is characterized by using a B-dot probe and proton defractmetory.

Strong-B field science

- ✓ Hydrodynamics and thermal transport with 0.1 kT.
- ✓ B-assisted central ignition and fast ignition with 1 kT.
- ✓ Atomic physics with >10 kT.
- ✓ High energy astrophysics with >100 kT.

Plasma hydrodynamics under strong magnetic field

- ✓ A thin plastic foil is accelerated by laser beams under strong magnetic field.
- ✓ Flying velocity of the laser-driven plastic foil is 50% faster in the magnetic field compared to that in normal conditions.
- ✓ Growth of hydrodynamic instability may be accelerated in the strong magnetic field.

Thermal transport under strong magnetic field

- ✓ Anisotropic thermal conduction plays important roles in the magnetized plasma.
- ✓ Anisotropic thermal conduction can be studied more directly by using a low-density foam target.

A variety of new plasma science with kilo-tesla magnetic field.

ILE, Osaka

> 1000 kT — **High Energy Astrophysics**

$r_{ce} < l_{Planck}$

100 kT — **Atomic physics**

$r_{ce} < \lambda_{de\ Broglie}$

10 kT — **Suppression of relativistic instability**

$\omega_{ce} > \omega_L$ (λ_L = 1 μm)

1 kT — **Fast Ignition & Central Ignition Laser Fusion**

0.1 kT — **MHD Hydrodynamics**

Strong-*B* Science @ 0.1 kT

Hydrodynamics of a HED plasma under strong B-field is important in ICF and astrophysics.

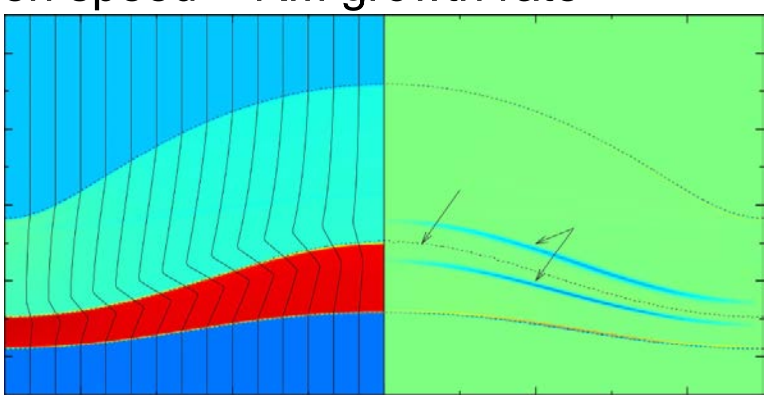
ILE, Osaka

RM instability in strong-B

Vorticity of the Rechtmyer-Meshkov instability carried by the Alfven wave.

Alfven speed << RM growth rate

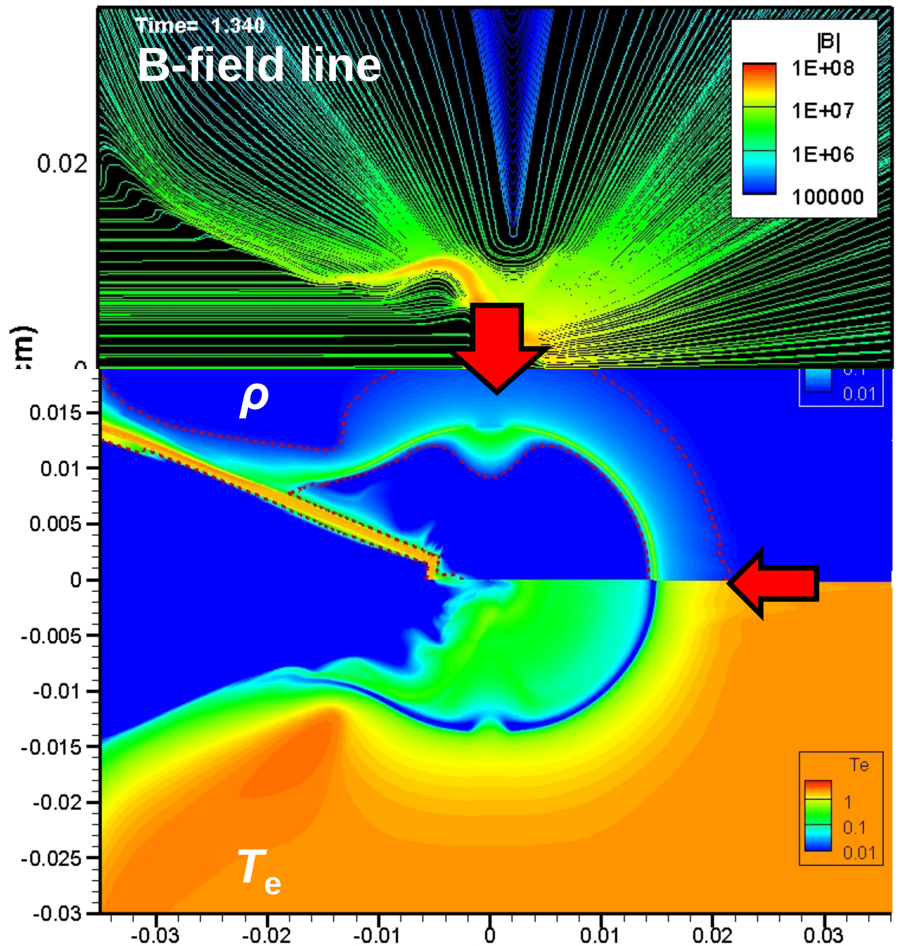
Alfven speed > RM growth rate



Presentation by Dr. Sano (S8-6)

Laser Driven Implosion w/strong-B

The non-isotropic thermal transport seeds low-mode non-uniformity.

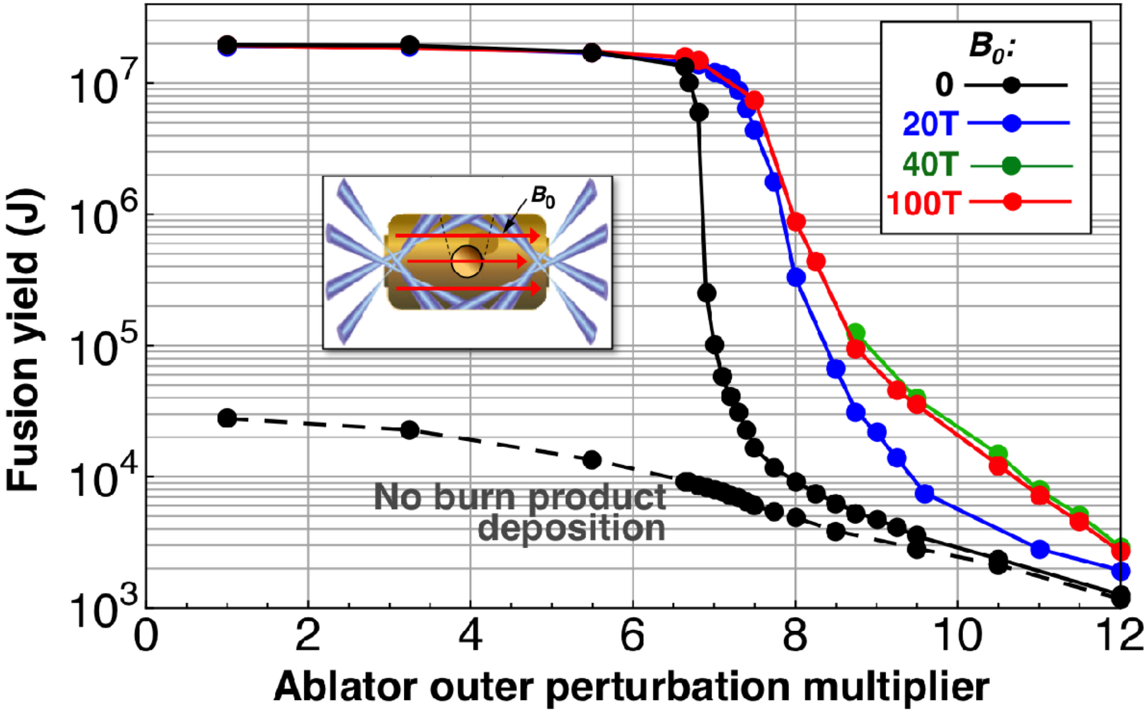


Presentation by Dr. Nagatomo (20aC1-1)

Strong-*B* science @ 0.1 kT

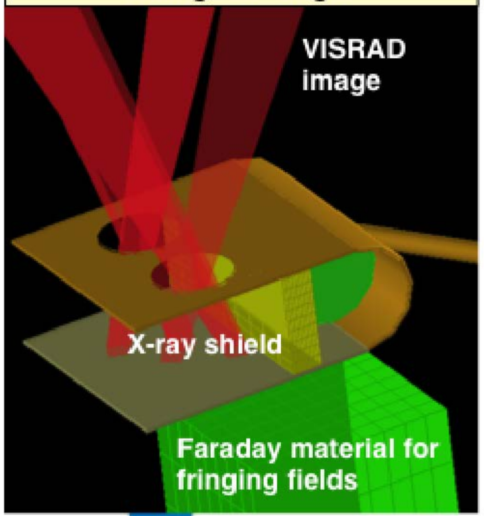
It is very exciting for me that Japan can contribute to the development of B-assisted ignition scheme.

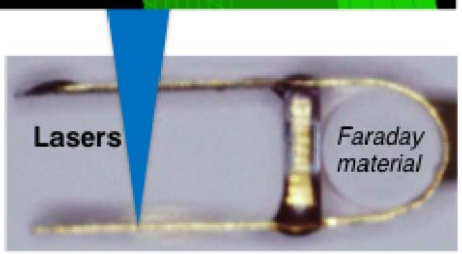
ILE, Osaka



NIF target fusion yield versus multiplier on the amplitude of capsule outer surface perturbation under initial seed magnetic fields from 0 to 100 T. The dashed line shows the fusion yield for B_0=0 with all fusion burn products allowed to escape without energy deposition (LASNEX 2-D radiation-hydrodynamic simulations)

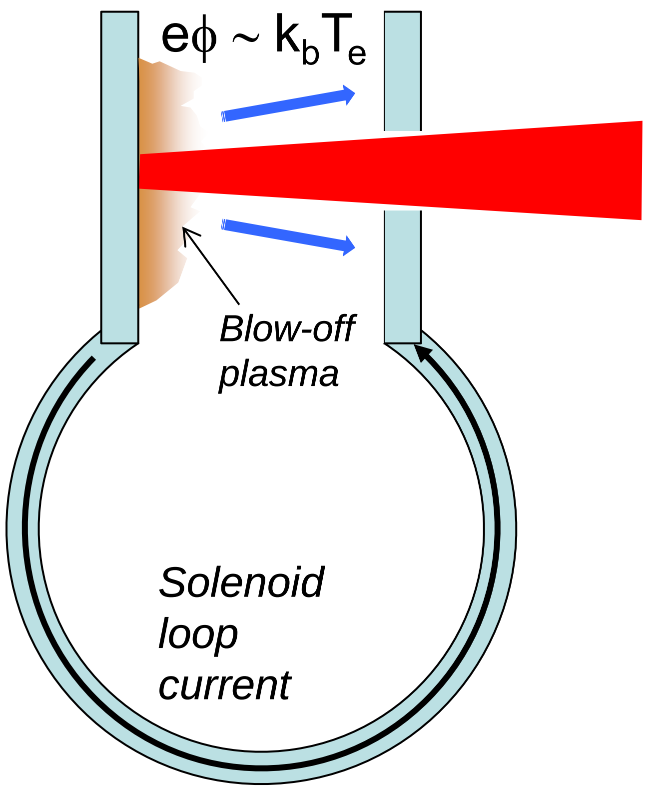
Omega-EP target

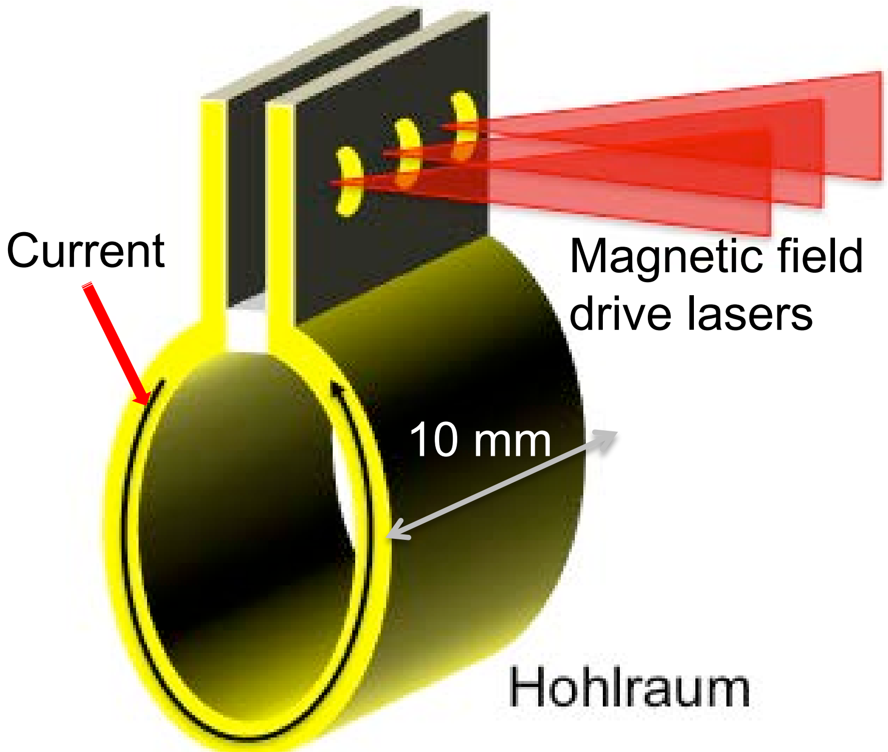




Laser-driven magnetic field generation schemes can provide ~100 T on ns-timescales

Laser driven plasma sheath creates voltage source for current



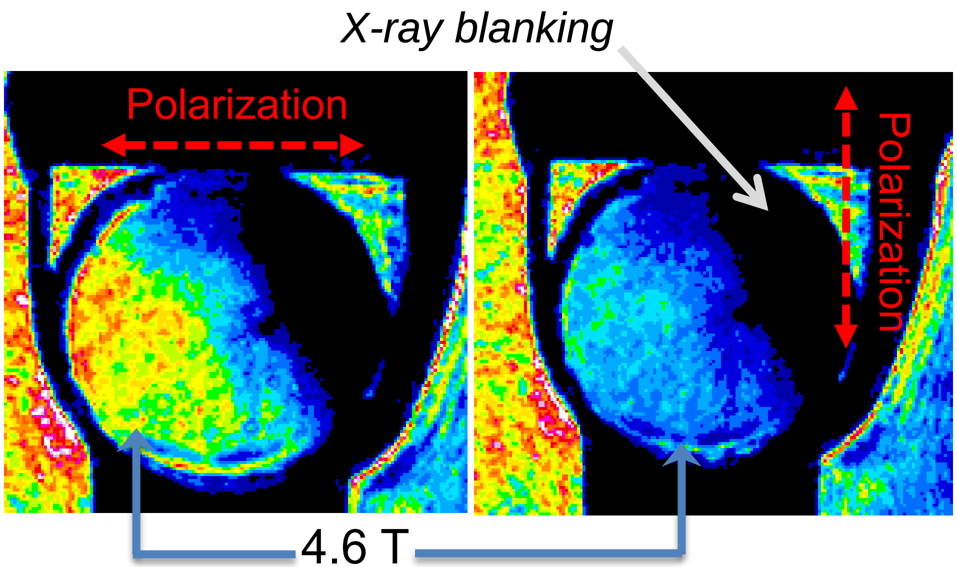


- Alternative to pulsed power
- Fast rise time ($\leq \tau_{laser}$)
- Integrated into the target

This is similar to a ConA target platform with backlighter configuration

Experiments on Omega-EP have successfully produced > 10 T fields

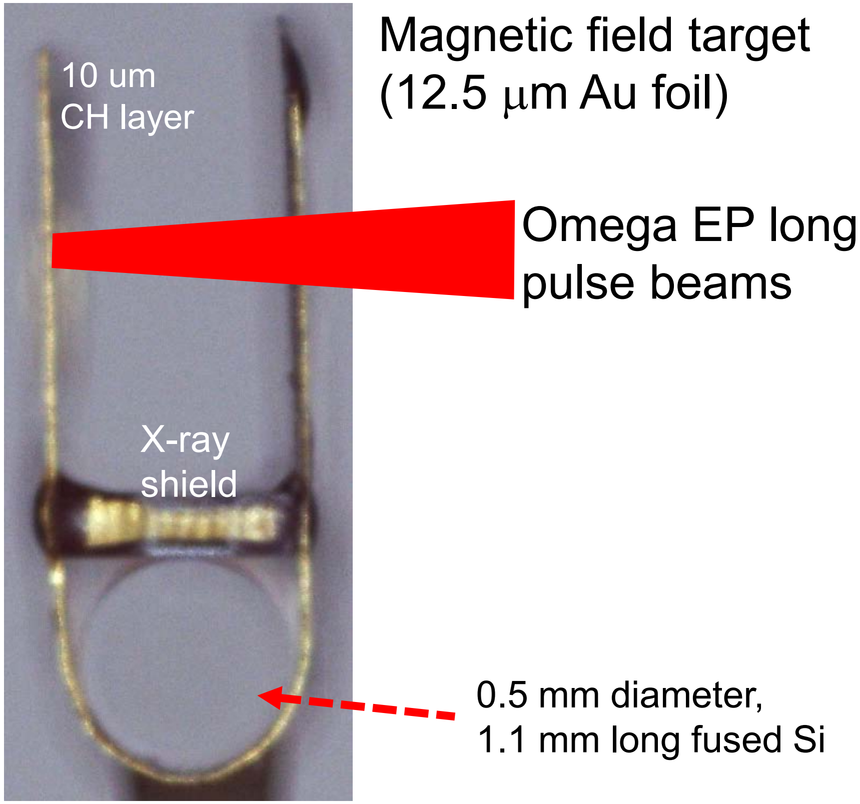
- The axis of the loop is parallel to the Omega EP 4ω probe to allow Faraday rotation measurements along the axis



$$I = I_0 \cos^2(\theta)$$

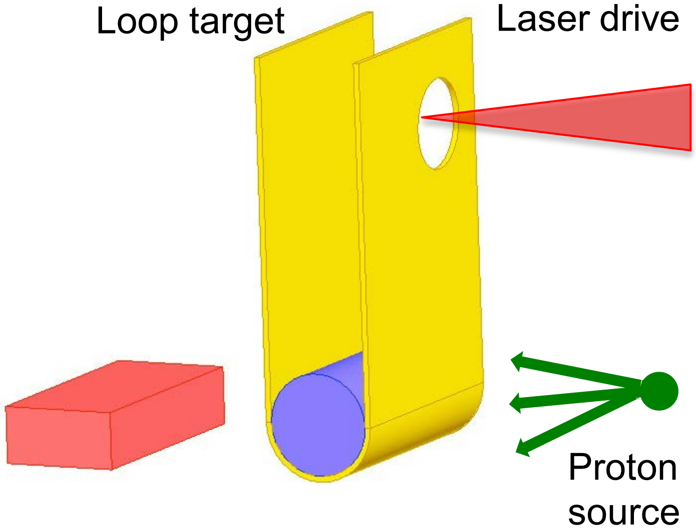
Faraday rotation angle $\theta = Blv$

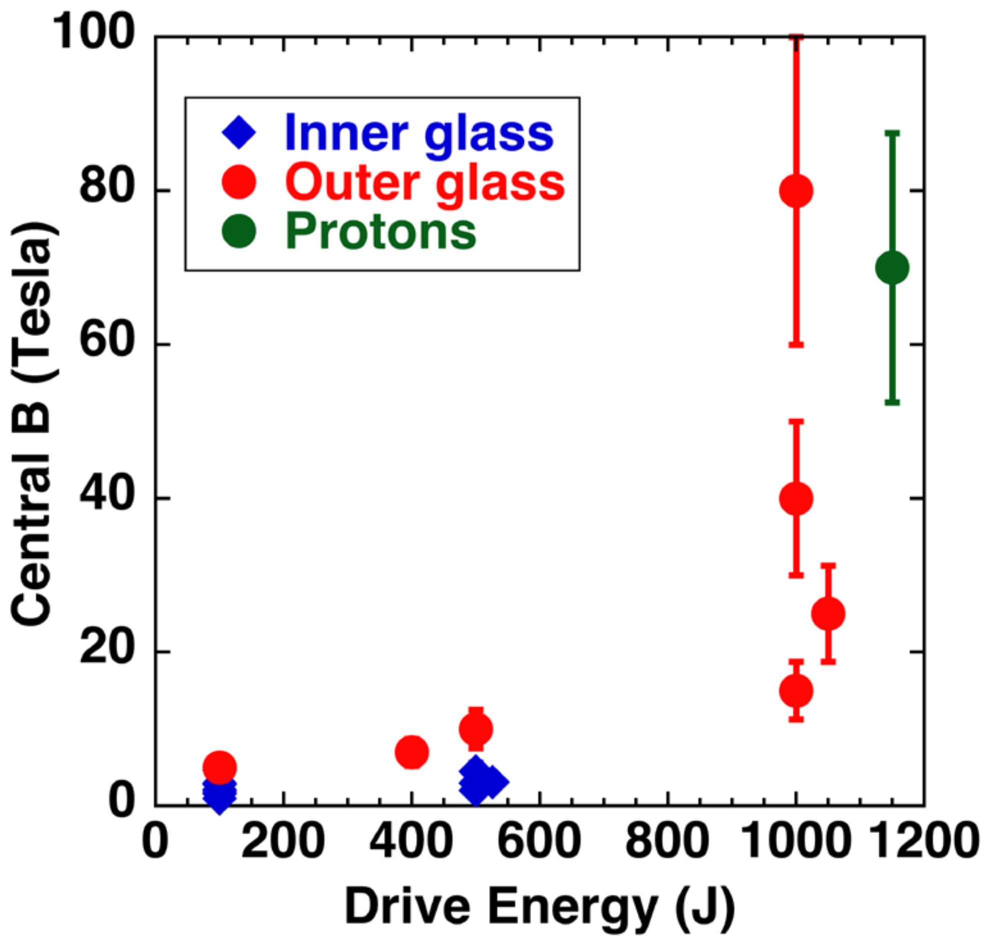
v = Verdet constant ~ 1.5°/T/mm (SiO_2 at 263 nm)



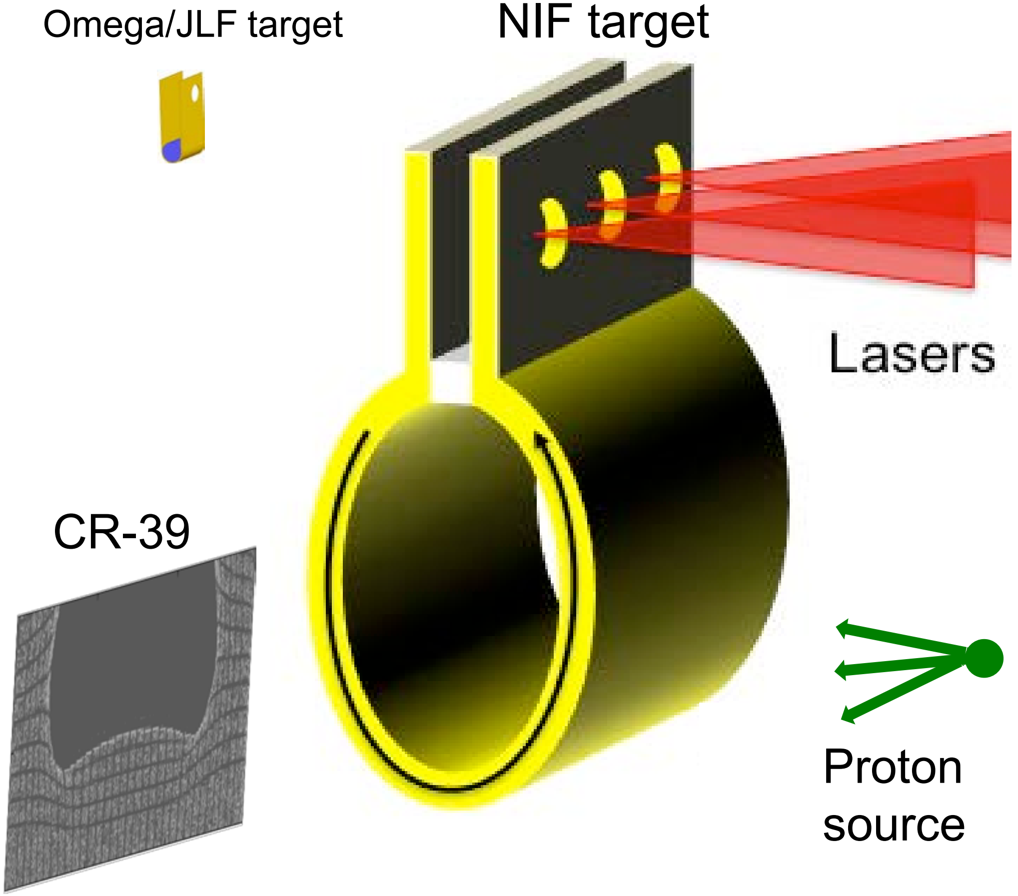
Scaling to NIF hohlraum volumes requires >10 kJ of laser drive

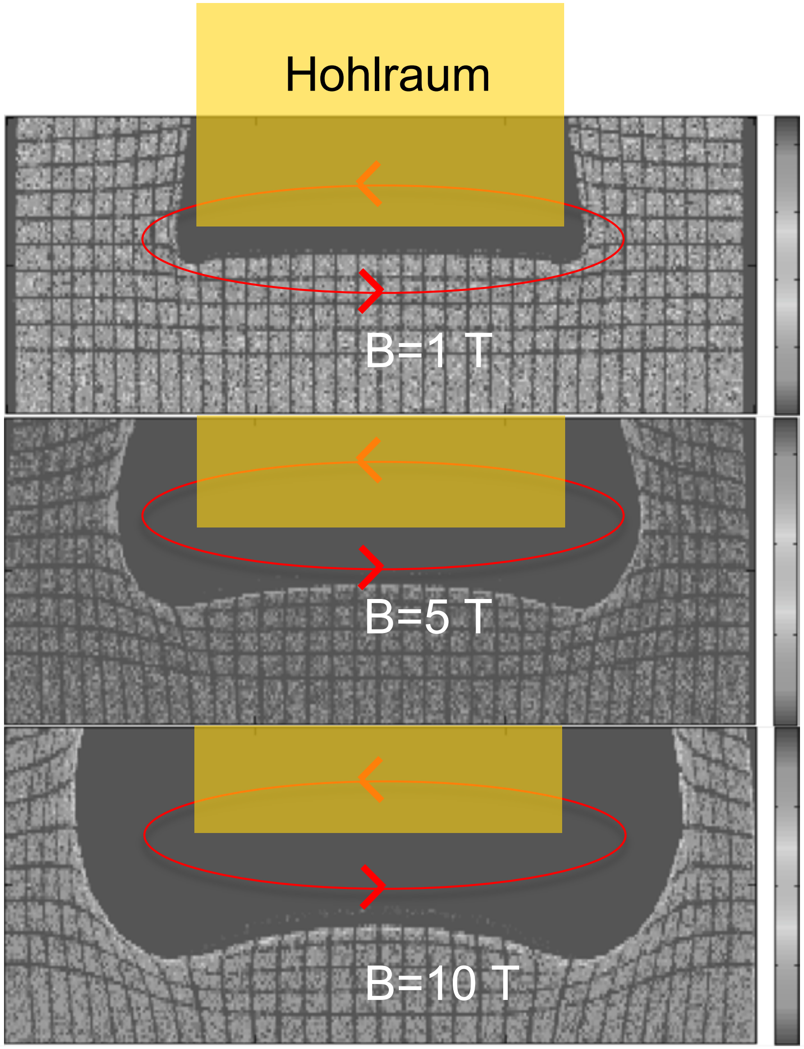
We have scaled the axial field up to 80 T in a ~mm^3 volume at Omega EP





Proton deflectometry in the fringing magnetic field allows inference to the axial field





FABS/NBI, SXI, FFLEX, DANTE, GXD's

Thomson scattering, Rogowski coil, Voltage measurement

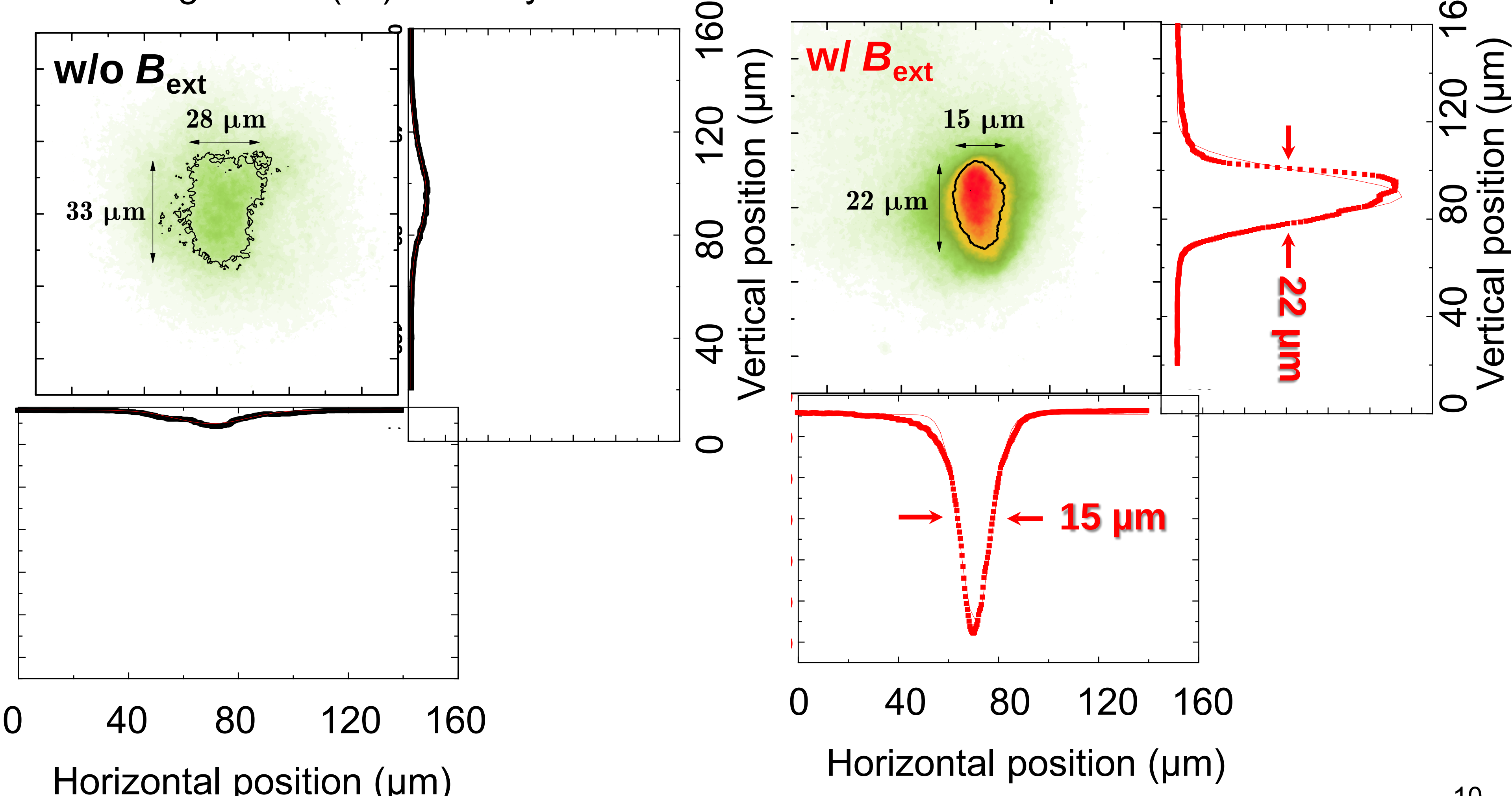
Laser-generated REB was pinched by externally imposed kT magnetic field.

ILE, Osaka

Santos *et al.*, Fr.O.3.2

Spatial Profile of Coherent Transition Radiation

Significant (x8) intensity enhancement and small hot spot were observed.

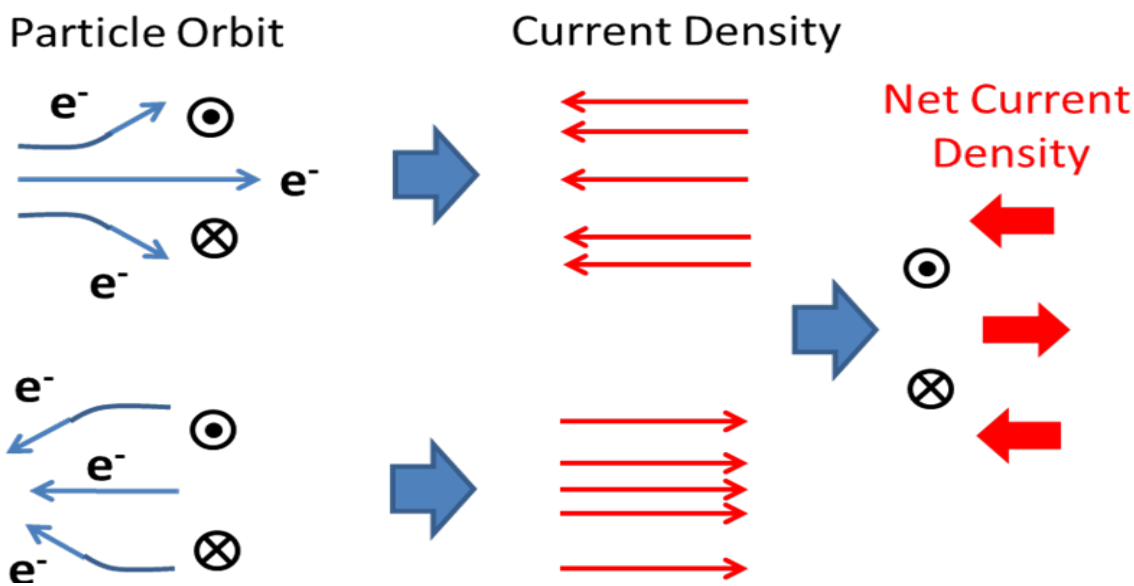


Weibel instability, source of REB divergence, can be suppressed by external magnetic field.

ILE, Osaka

Weibel instability in counter streaming electrons

Initial spatial non-uniformity of B-field makes local current density non-uniform.
The non-uniform current density amplifies B-field non-uniformity.



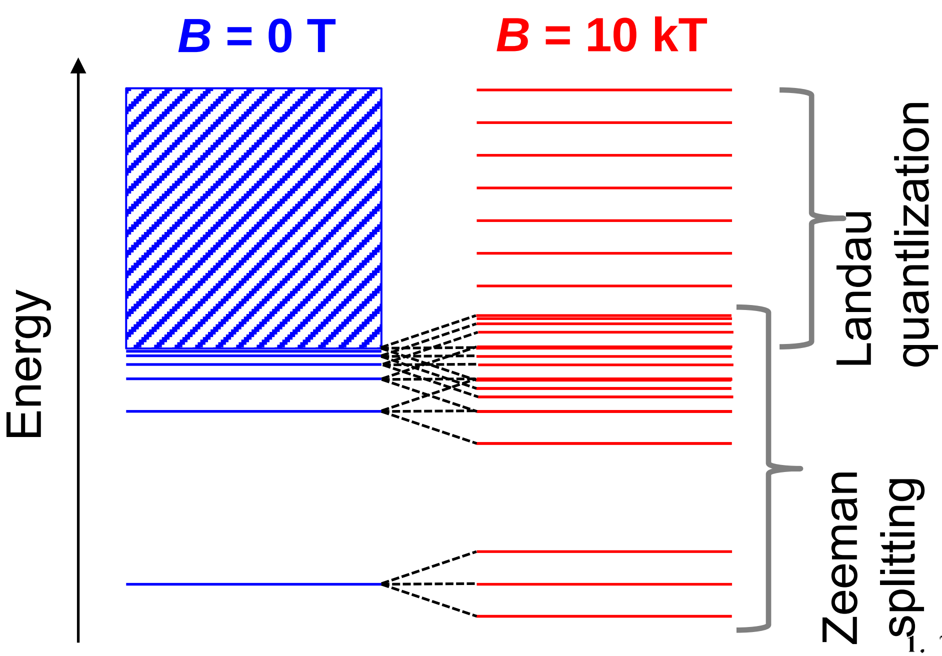
Strong-*B* science @ 10 kT

Landau quantization gap and Zeeman splitting energy reach a few eV under 10 kT field.

ILE, Osaka

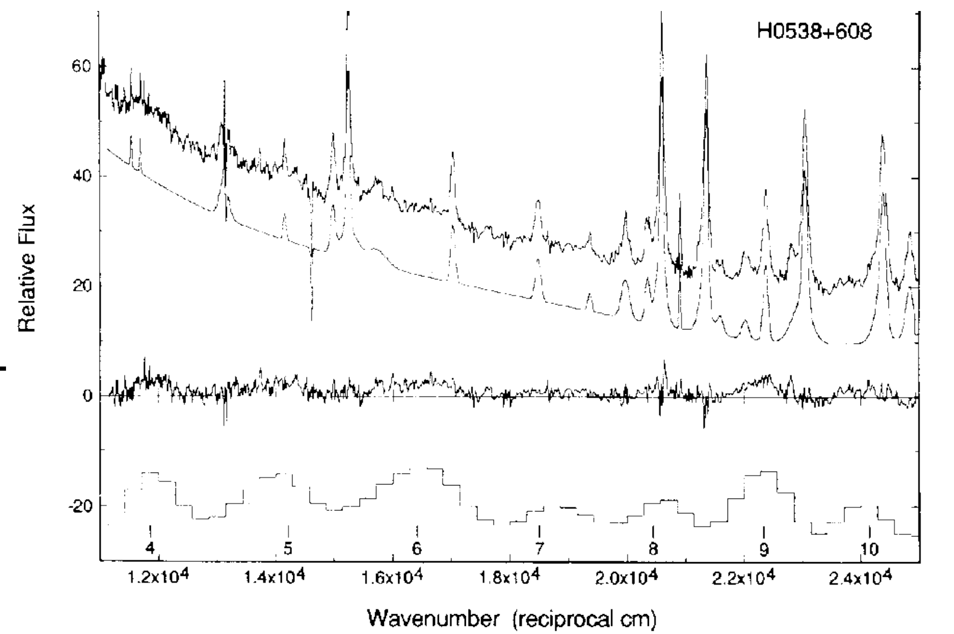
Energy diagram under B-field

Exotic atomic energy state can be generated in our laboratory with 10 kT magnetic field



Emission spectrum from white dwarf

Landau level and Zeeman splitting are good measures of magnetic field in stars.



1. The spectrum of H0538 + 608 from 4000 Å to 9090 Å plotted against wavenumber in at the top. Longer wavelengths are on the left, shorter on the right. Beneath this spectrum is a

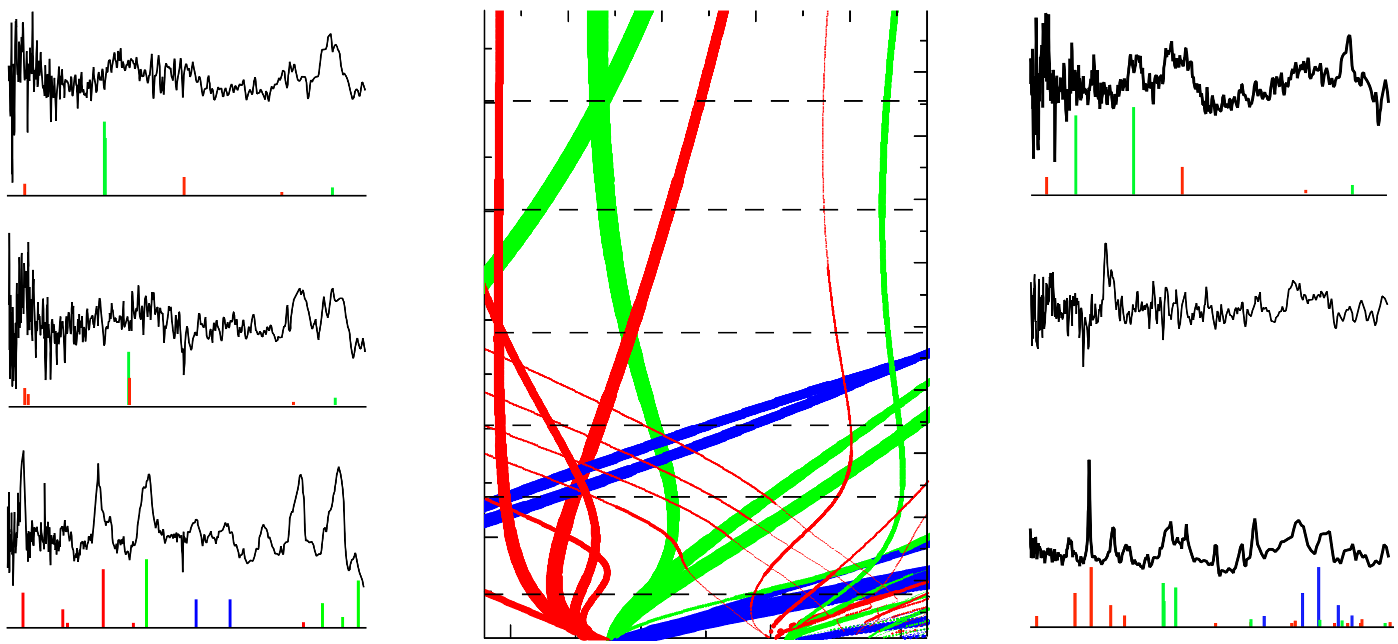
Presentations by Dr. Iwakiri (S8-3)

Strong-B science @ 10 kT

ILE, Osaka

2nd order Zeeman effect becomes significant with 10s kT of magnetic field.

$$H=\underbrace{\frac{\mathbf{p}^2}{2m_e}-\frac{e^2}{kr}}_{\text{Hydrogen atom}}+\underbrace{\frac{1}{2}\left(\mathbf{p}\cdot\mathbf{A}+\mathbf{A}\cdot\mathbf{p}\right)}_{\substack{1^{st}\text{ Zeeman effect}\\ =1/2\text{ m B}}}+\underbrace{\frac{1}{2}\mathbf{A}^2}_{\substack{2^{nd}\text{ Zeeman effect}\\ \neq 1/2\text{ m B}}}$$



B. N. Murdin et al., Nature Communications, Vol. 4, p. 1469 (2013).

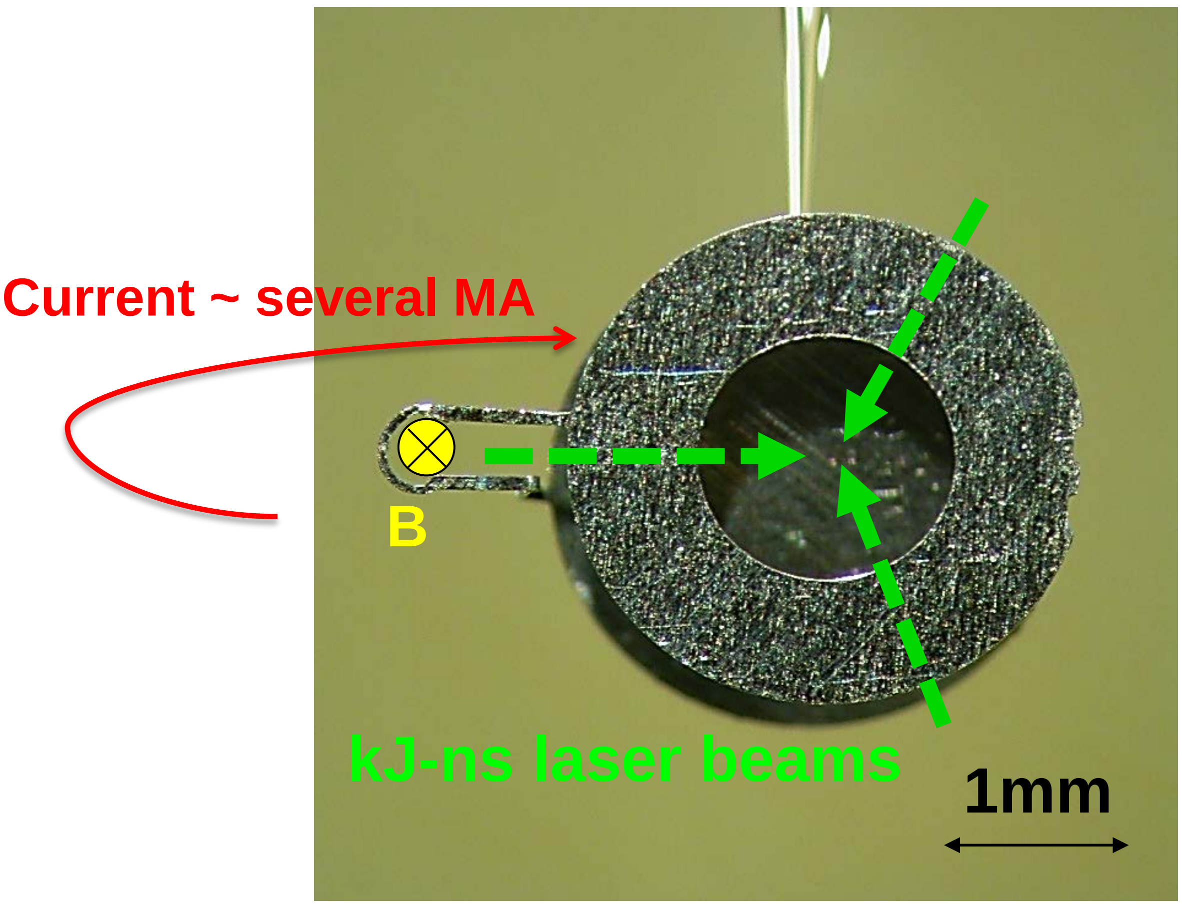
Guiding REB campaign

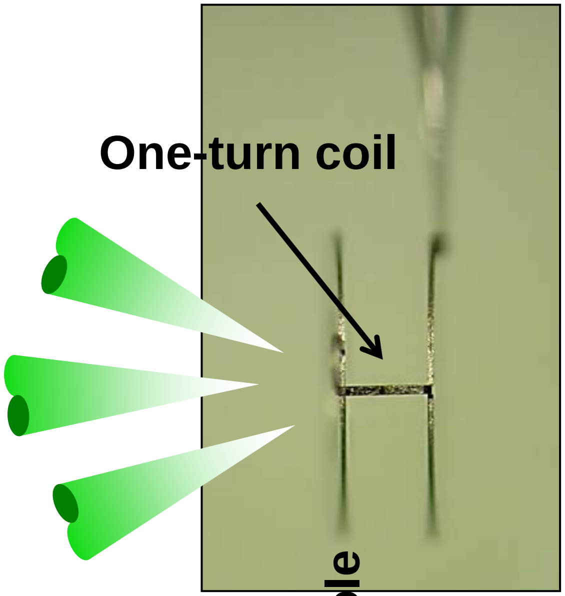
1 kT B-field* was generated with a capacitor-coil target# and a ns-kJ laser (GEKKO [JAPAN]* & LULI [FRANCE]$) .

ILE, Osaka

#H. Daido *et al*., PRL (1985), C. Courtois *et al*., JAP (2005).
*S. Fujioka *et al*., Sci. Rep. (2013).
$J. J. Santos *et al*., NJP (2015).

Photo of a capacitor-coil target

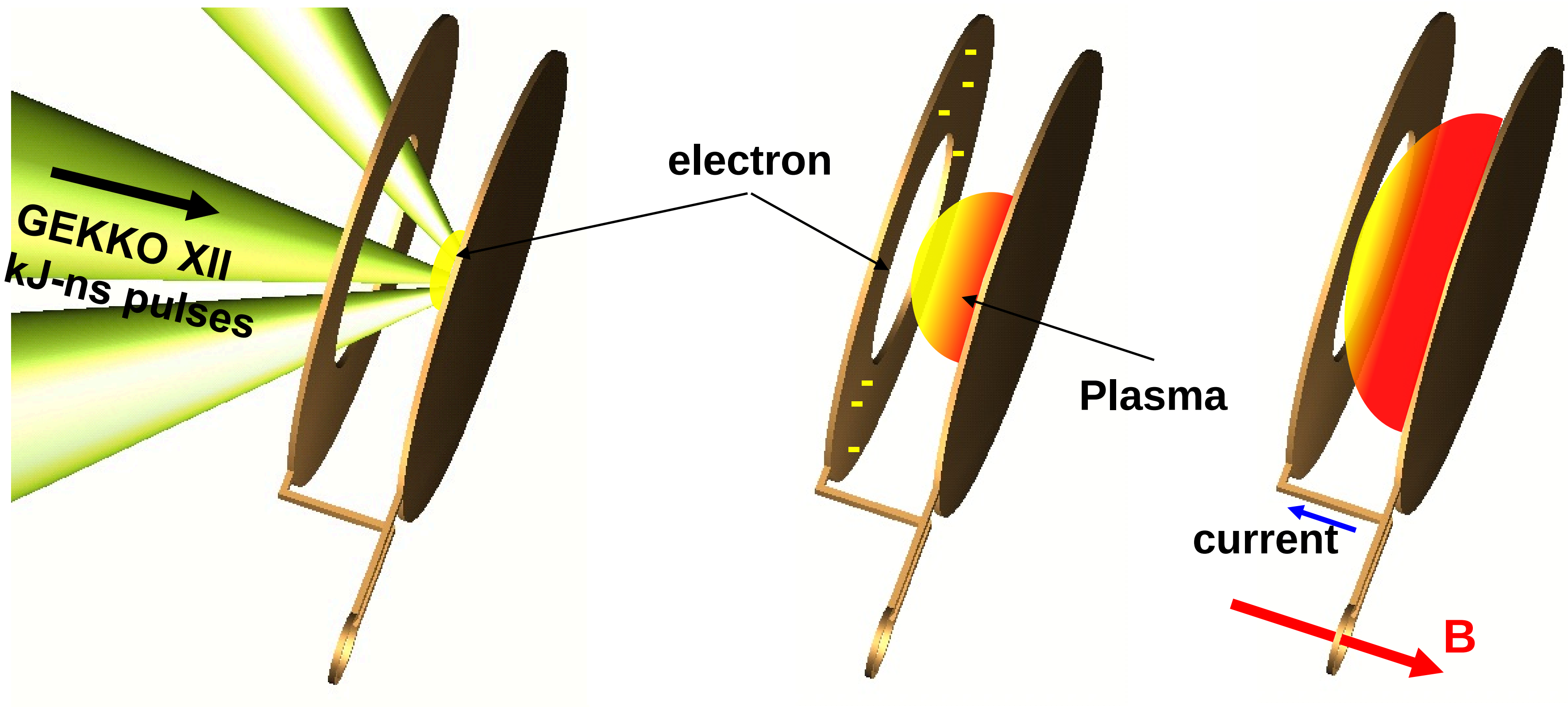




Movement of non-thermal hot electrons between the disks drives electric current in the wire.

ILE, Osaka

Non-thermal hot electron generation	Electrons accumulates on the disk	Current is driven in wire



Guiding REB campaign

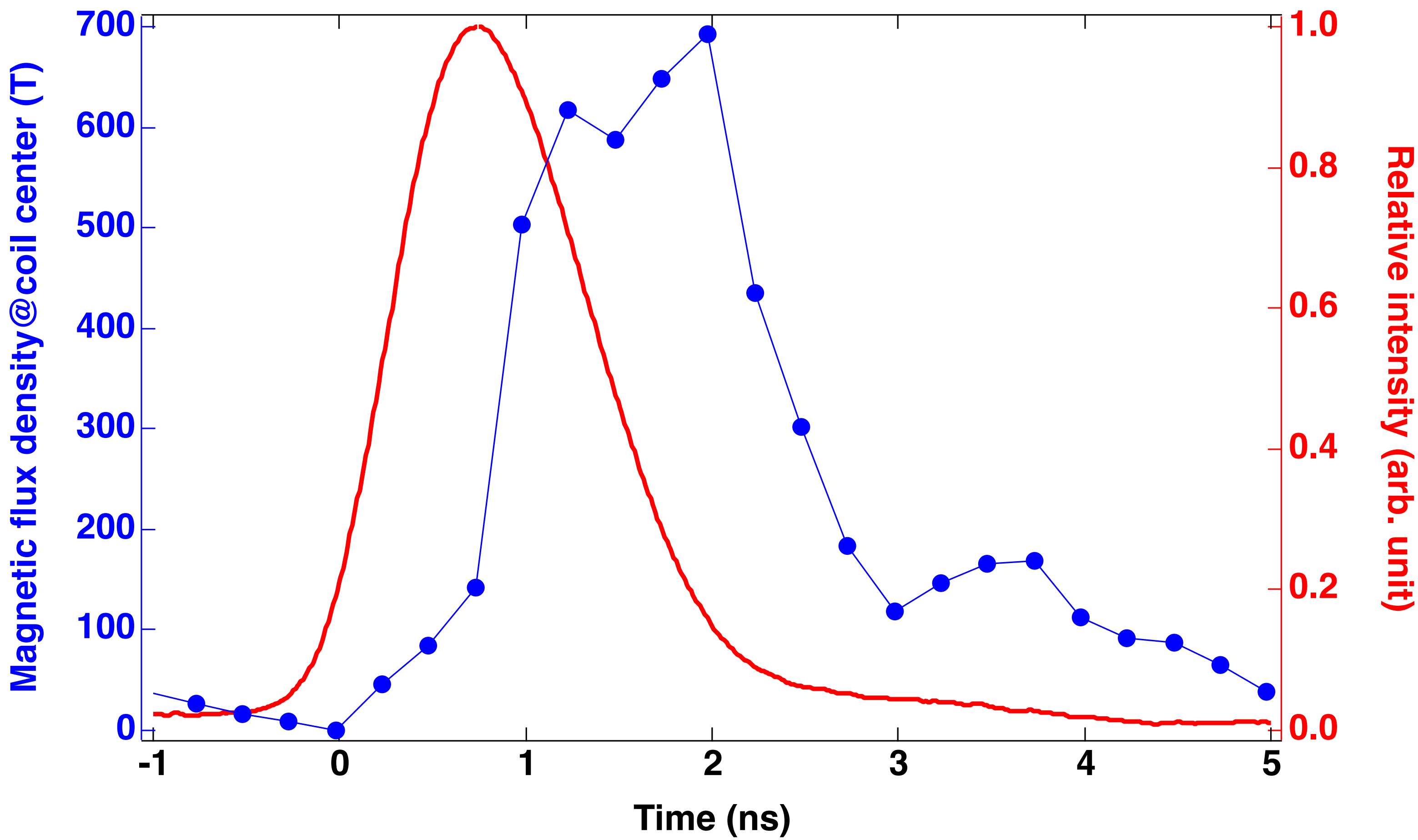
Capacitor-coil target generates a B-field pulse having 600 T of the maximum strength and 2 ns of FWHM.

ILE, Osaka

Law *et al*., in preparation

Temporal history of B-field measured with B-dot probe

700T of the peak magnitude and 2 ns of the duration



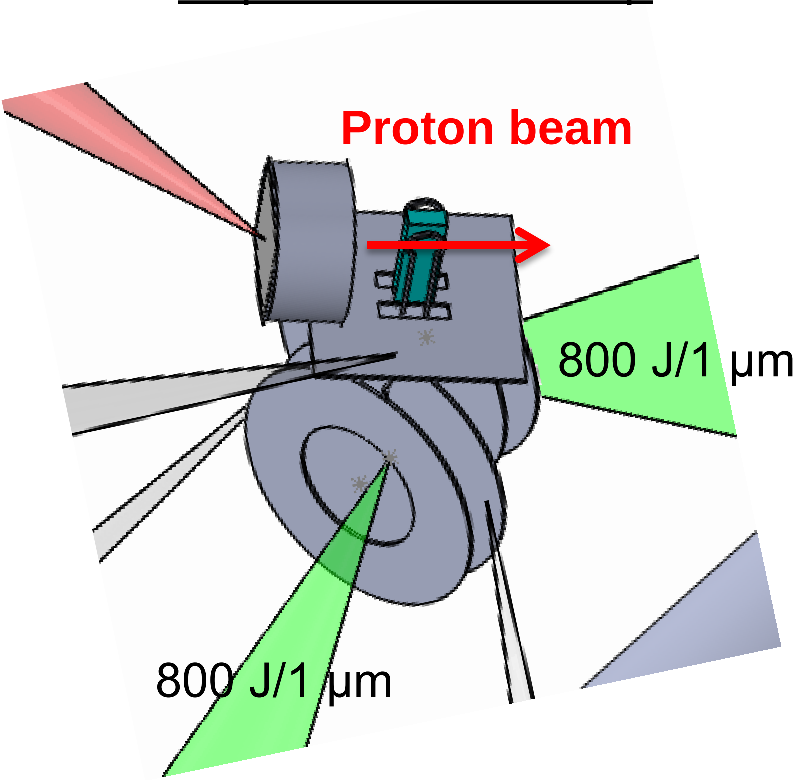
Guiding REB campaign

600 T of the maximum strength was measured directly with proton deflectmetory.

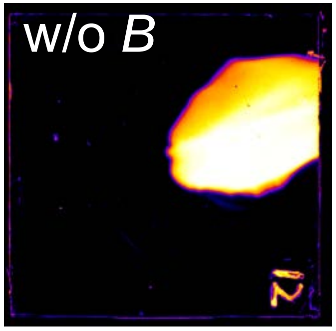
ILE, Osaka

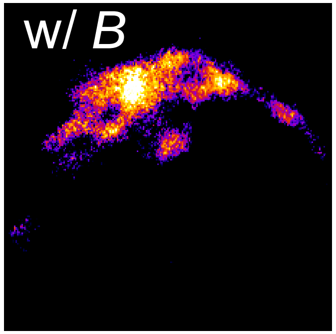
Law *et al.*, in preparation

Experimental set-up

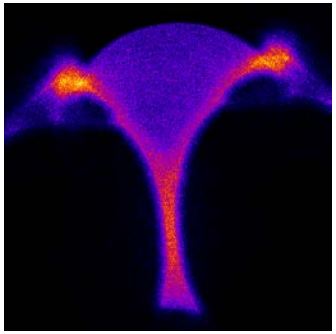


Proton pattern on RCF

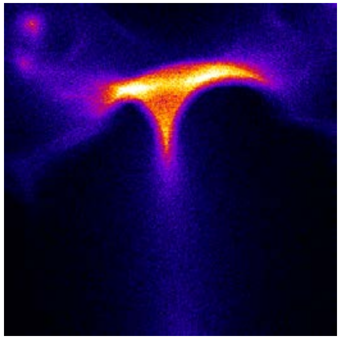




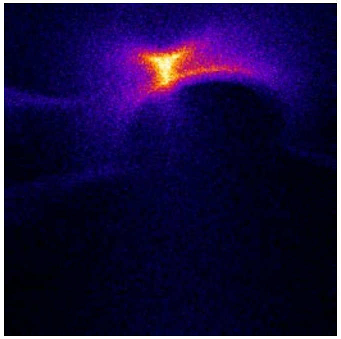
Simulation (MC+ RADIA)



B_z= 245 T



B_z= 611T



B_z= 978 T

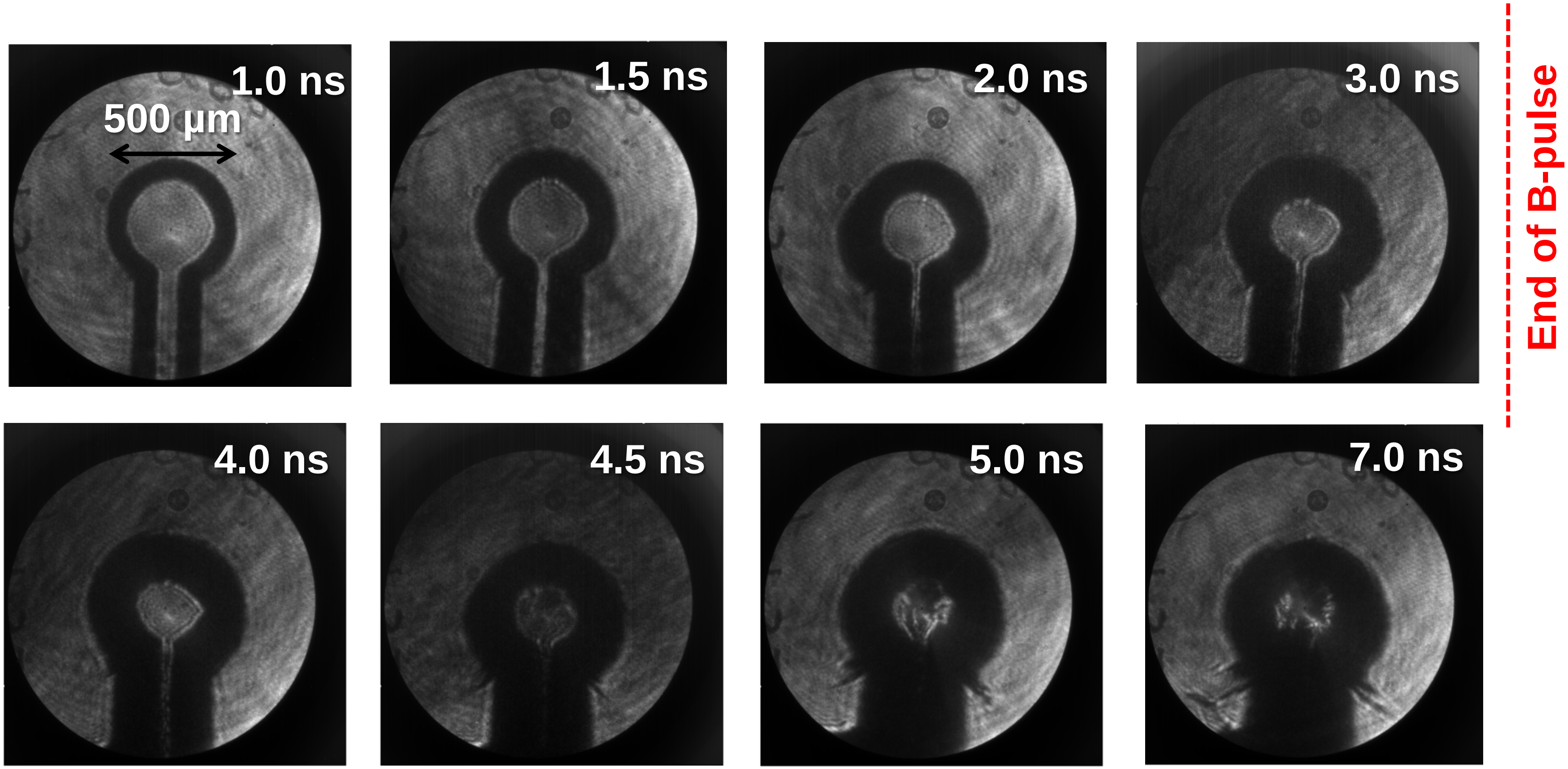
Guiding REB campaign@LULI

The central hole of a coil remains during B-pulse duration (0 – 3 ns).

ILE, Osaka

2D shadowgraph of exploding coil

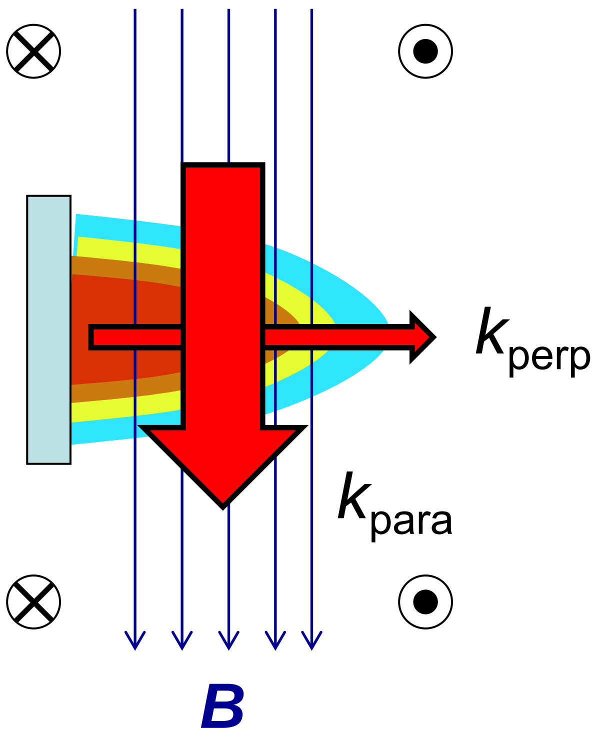
Gate width of 2D shadow is 250 ps.



Thermal conductivity becomes anisotropic under strong B-field.

ILE, Osaka

Thermal conductivity in parallel B-field



Braginskii coefficient

$$k_{para} = k_{w/o\ B}$$

$$k_{perp} = k_{w/o\ B}/(1+(\omega_{ce}\tau_e)^2)$$

$k_{w/o\ B}$: conductivity (w/o B)
ω_{ce} : elec. gyrofrequency
τ_e : elec. collisional time

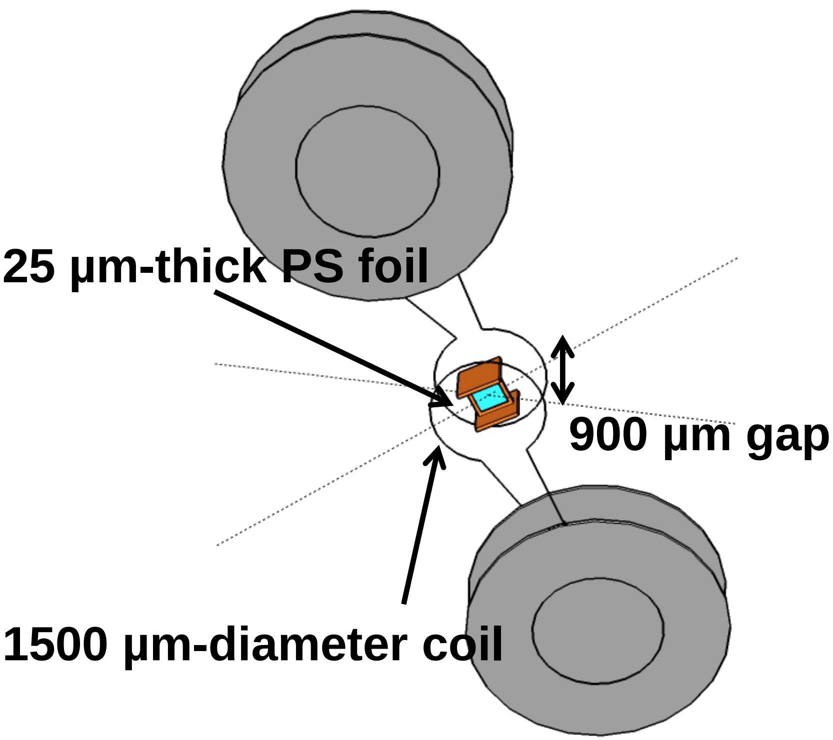
T_e = 100 eV, n_e = 9 x 10^{21} cm^{-3}
$\omega_{ce}\tau_e \sim 1$

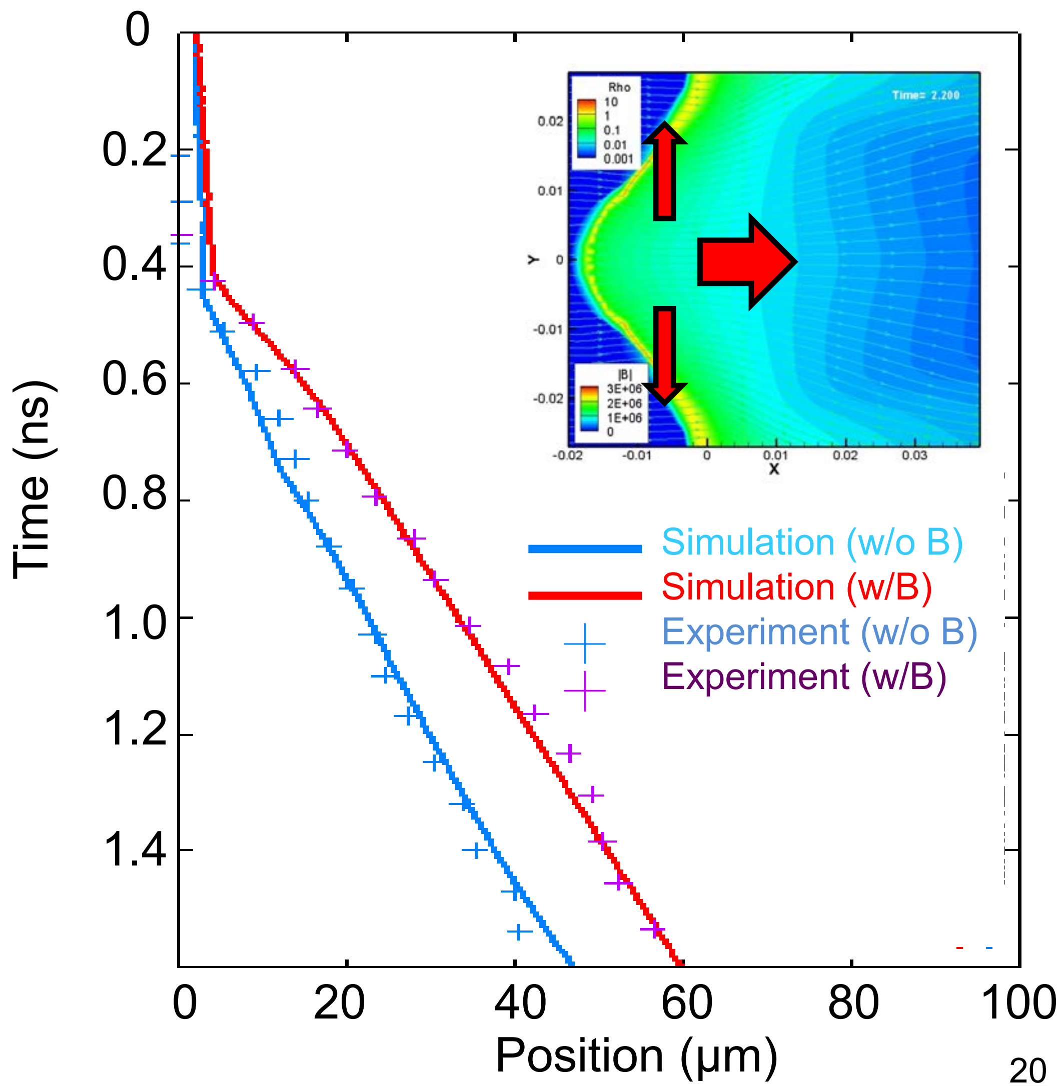
Hydrodynamics in strong B-field

Uniform magnetic field was generated for this experiment by using a Helmholtz-type coil-capacitor target.

ILE, Osaka

Perpendicular B-field Geometry





Perturbation growth is affected by the externally imposed B-field owing to anisotropic thermal transport.

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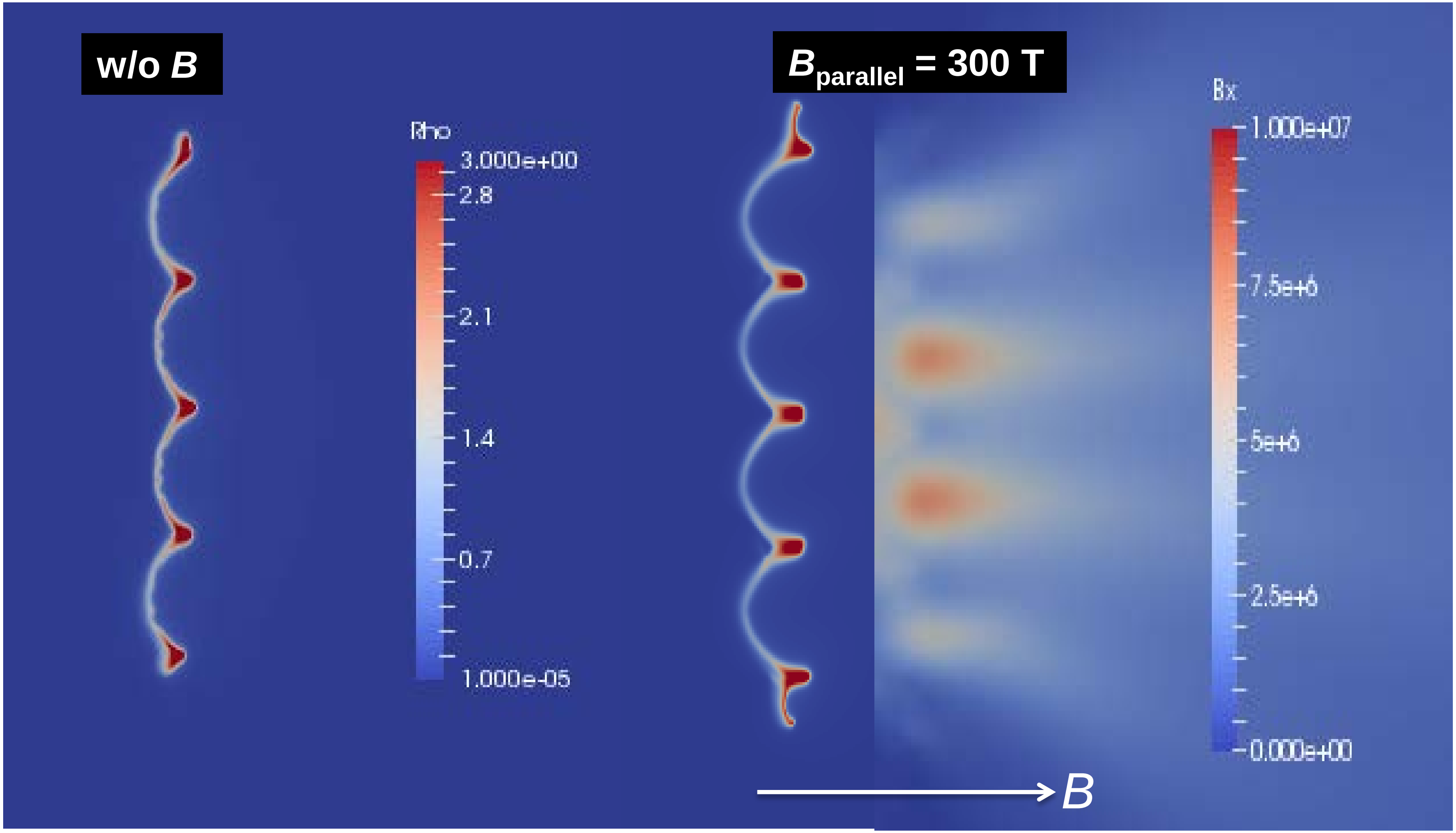
Hydrodynamic instability in strong external B-field

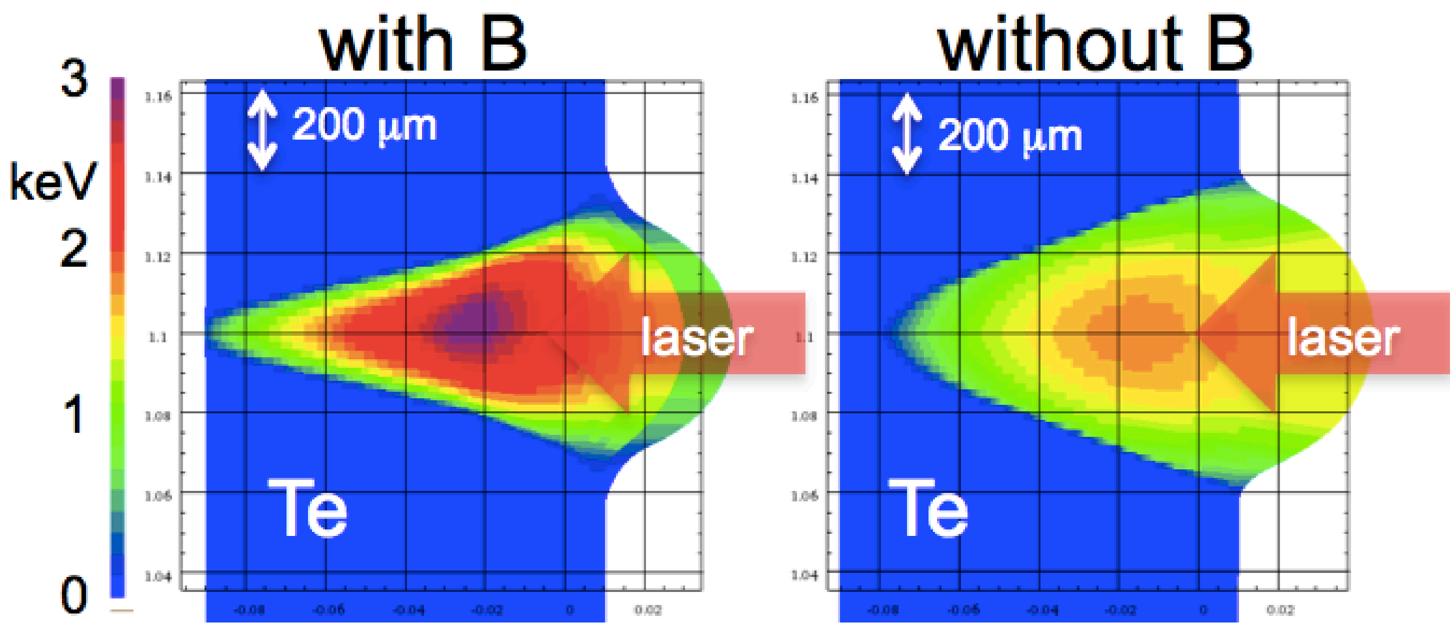


Anisotropic thermal transport can be studied by using low-density foam.

ILE, Osaka

P. Nicolai et al., Private Communication.

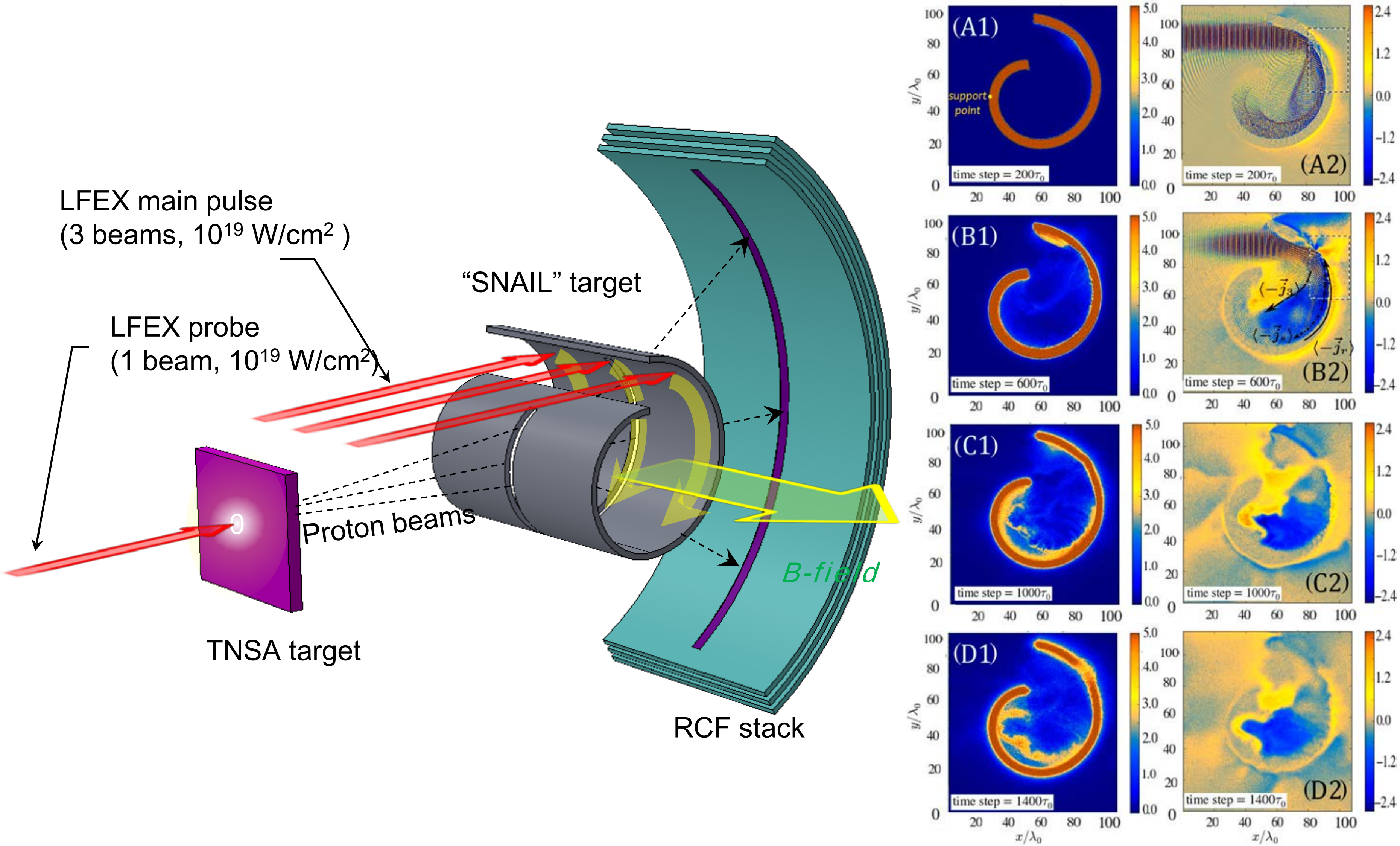
Heat wave propagation under magnetic field.



Toward 10 kT

Strongest magnet on the earth can be generated with a SNAIL target and LFEX laser.

ILE, Osaka



Dr. Korneev (Nuclear Research National University, Russia)

SUMMARY

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Thermal transport under strong magnetic field

- ✓ Anisotropic thermal conduction plays important roles in the magnetized plasma.
- ✓ Anisotropic thermal conduction can be studied more directly by using a low-density foam target.

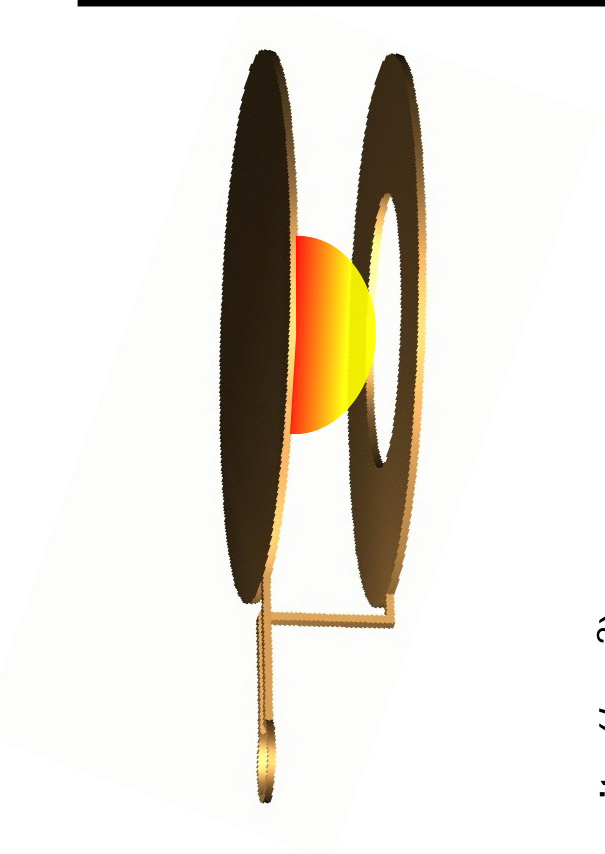
Strong-*B* Generation

Electrons traveling with a plasma expansion front# are accumulated on the capacitor disk.

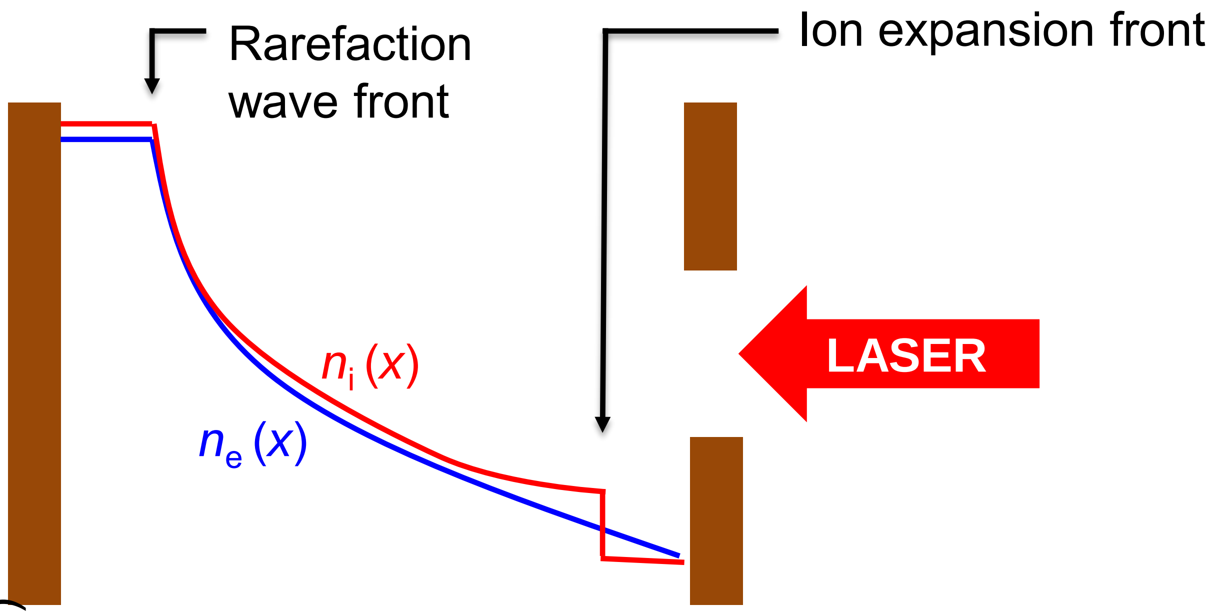
ILE, Osaka

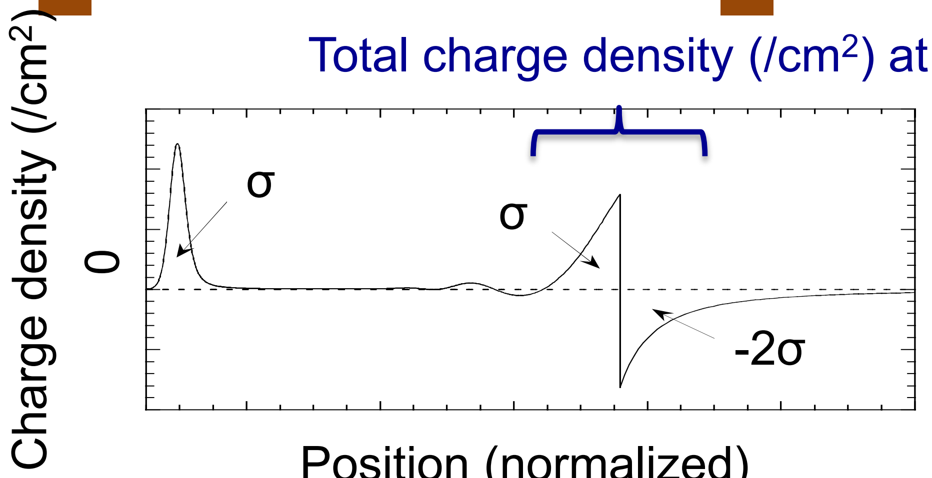
#P. Mora, PRL (2003).

Drawing of C-C target



Plasma profile between disks





Electric potential difference of the capacitor can be calculated with the isothermal expansion model#.

ILE, Osaka

#P. Mora, PRL (2003).

$$\sigma = \epsilon_0 E_{ss}$$

Total charge density at the ion front (C/m^2)

$$Q = \sigma S$$

Charge accumulated on the disk.
S is the size of the disk (m^2)

Temperature of hot electrons generated by resonance absorption

Time duration for that the ion front arrives at the accumulation disk.

$$E_{ss} = k_B T_e / e c_s t$$

Electric field at the ion front.

$$d = c_s t[2\ln(\omega_{pi} t) + \ln 2 - 3].$$

d is the distance between the disks.

V = 0.5 MV, I = 0.3 MA, and B = 750 T for 1 kJ with the model.

Magnetic reconnection with colliding externally-magnetized plasma plumes for the NIF

W. Fox, PPPL, **G. Fiksel,** U Michigan

A. Bhattacharjee, H. Ji, L. Gao, K. Hill, W. Deng, C. Liu, Princeton / PPPL

G. Fiksel, D. Barnak, P.Y. Chang, P. Nilson, S.X. Hu, LLE

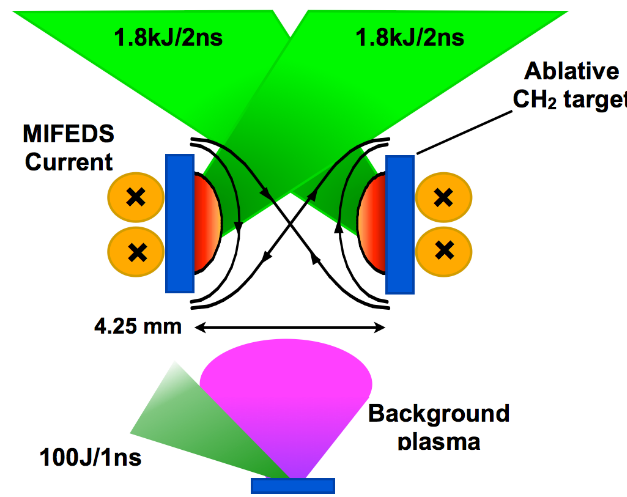
K. Germaschewski, University of New Hampshire

NIF B Fields Workshop, LLNL, 10/13/2015

Laser-driven reconnection experiments with externally applied fields developed for OMEGA EP

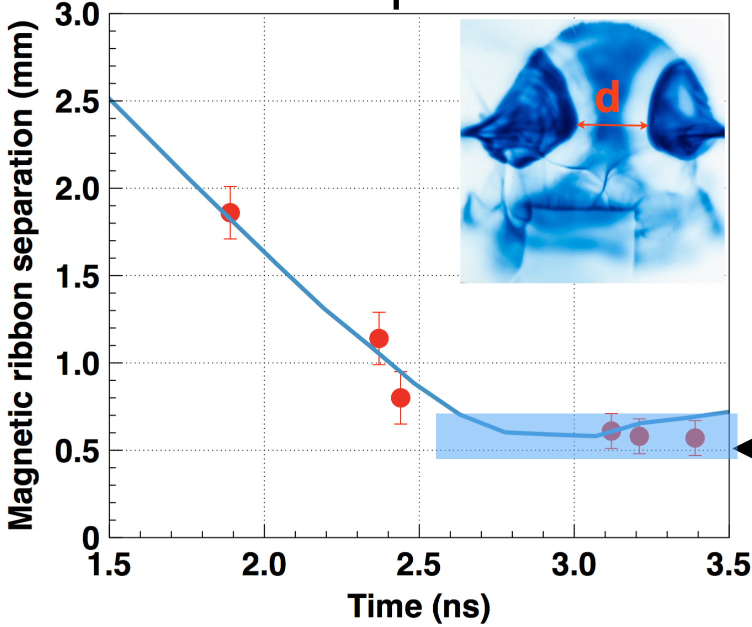
- Previous magnetic reconnection experiments have been developed, based on self-generated (Biermann battery) magnetic fields [Nilson PRL 2006, Li PRL 2007, Rosenberg Nat Comm 2014, Zhong Nat Phys 2010]
- A new method with externally-controlled B field experiments developed for OMEGA EP using MIFEDS. First experiments demonstrated current sheet formation [Fiksel PRL 2014].

- Some advantages of externally controlled B fields:
    - controlled application of B field, and initial condition. Possibly can store more magnetic flux into system than when self-generated
    - compare to"null" experiments, with parallel B fields (non-reconnecting topology), or zero B fields (observation of Weibel instability by Fox PRL 2013)
    - Amenable to 2-d end-to-end PIC simulations

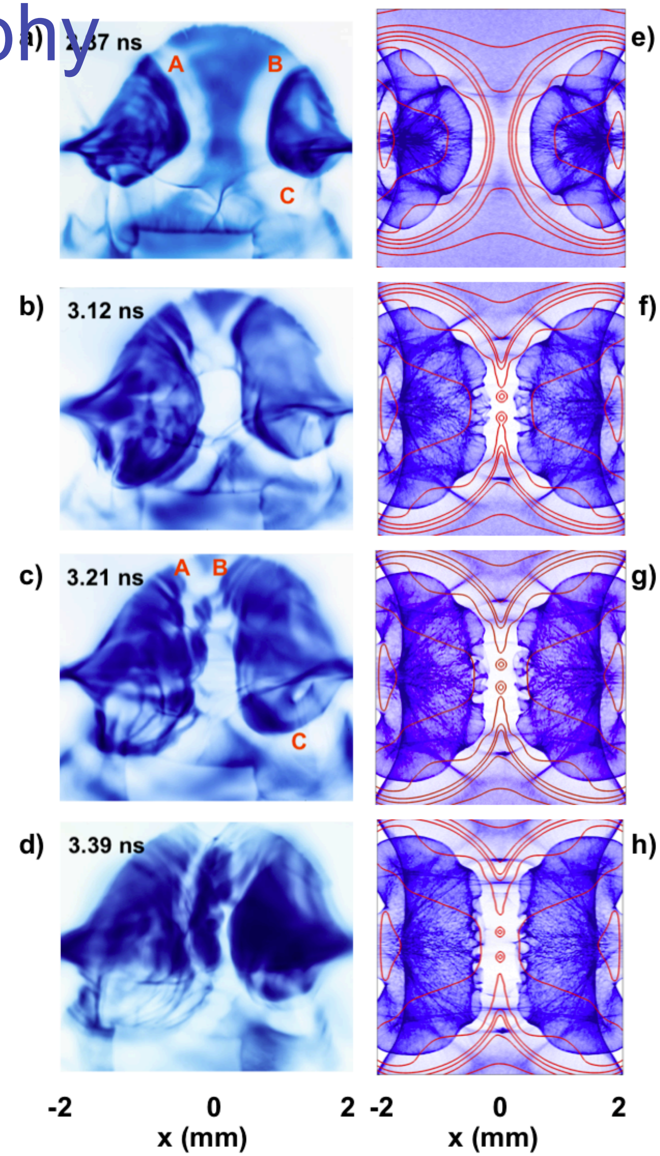


EP MIFEDS Reconnection and PIC simulations compared via synthetic radiography

Ribbon separation



Stagnation of current sheet at ion-scale



[G. Fiksel, WF, AB, et al “Magnetic Reconnection between Colliding Magnetized Laser-Produced Plasma Plumes” PRL (2014)]

2 page Physics summary (1)

Experiment: Magnetic reconnection of externally-applied B fields

Experiment: NIF Reconnection
Responsible Org: LLNL/LANL/SNL/LLE/etc
NIF shots from: Program, Disc Sci, other
Shot RI: Name of person
Engineer: Person / organization

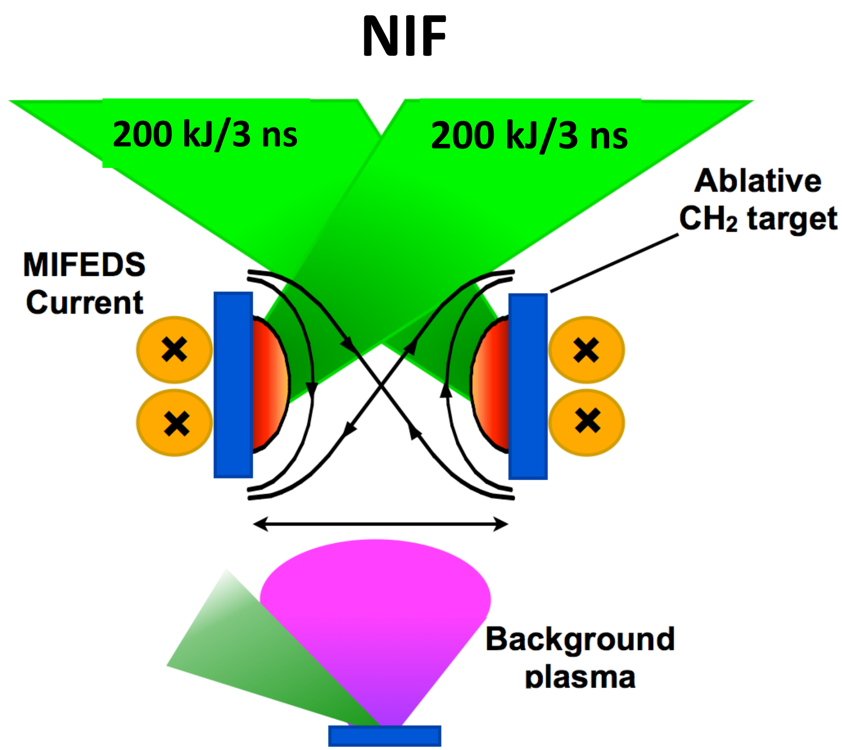
Experimental objectives: Observe reconnection rate, geometry of current layer.

Key physics related to having a B-field: Magnetic energy is stored in plasma, then liberated by reconnection and goes to heating plasma and energizing particles.

Expected results: Obtain magnetic reconnection at large system size and low collisionality. Compare results from EP to NIF.

Important aspects of the experiment:

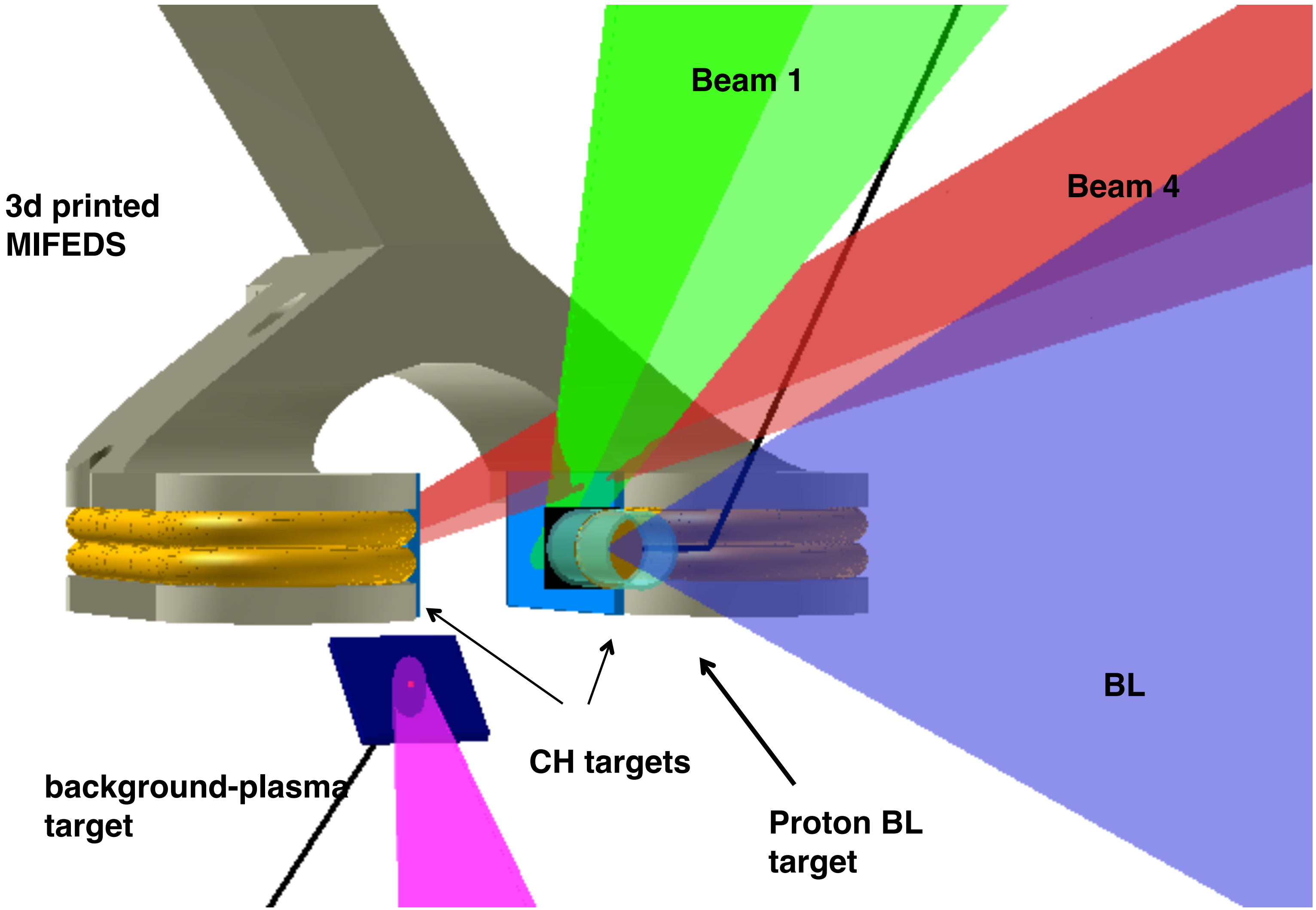
- **reversing B fields with peak B ~25 T**
- Can the experiment be done as a phased approach – with phased increases in B? **probably**



2 page Physics summary (2)

Experiment: Magnetic reconnection of externally-applied B fields

Setup on OMEGA EP. NIF similar, but using multiple overlapping beams on each target:



This experiment requires a B≥ 25 T and uniformity to 25%

Zero order considerations: NIF has ~100x the laser energy of EP. Therefore desire ~100x the B-field energy to accomplish a comparable experiment by keeping plasma beta constant. (And more B is even better.)

Scaling arguments: Plasma energy directly maps to figures of merit for a reconnection experiment. (*basically-no-free-lunch*)

$E = nTL^3 \sim S^{0.25} * (\lambda_{mfp}/L)^{0.25} * (L/d_i)^3$ ($S = LV_A/\eta$ = Lundquist number)

E.g., could scale to NIF by increasing

- ***T_e*** - more collisionless, lower resistivity - then require higher *peak* B field
- ***L*** - large system size - then you require larger B *volume*

I chose: $L_{NIF} = 3\ L_{EP}$; $n_{NIF} = 3\ n_{EP}$; $T_{;NIF} = 4\ T_{EP} \rightarrow S_{NIF} \sim 10^5$; $L/di \sim 150$. (Excellent parameters!). Implies $B_{NIF} \sim 2.5\ B_{EP}$ **~ 25 T**. $(B^2V)_{NIF} \sim 200\ (B^2V)_{EP}$

Future dedicated (*large)* simulations could quantitatively address the design parameters.

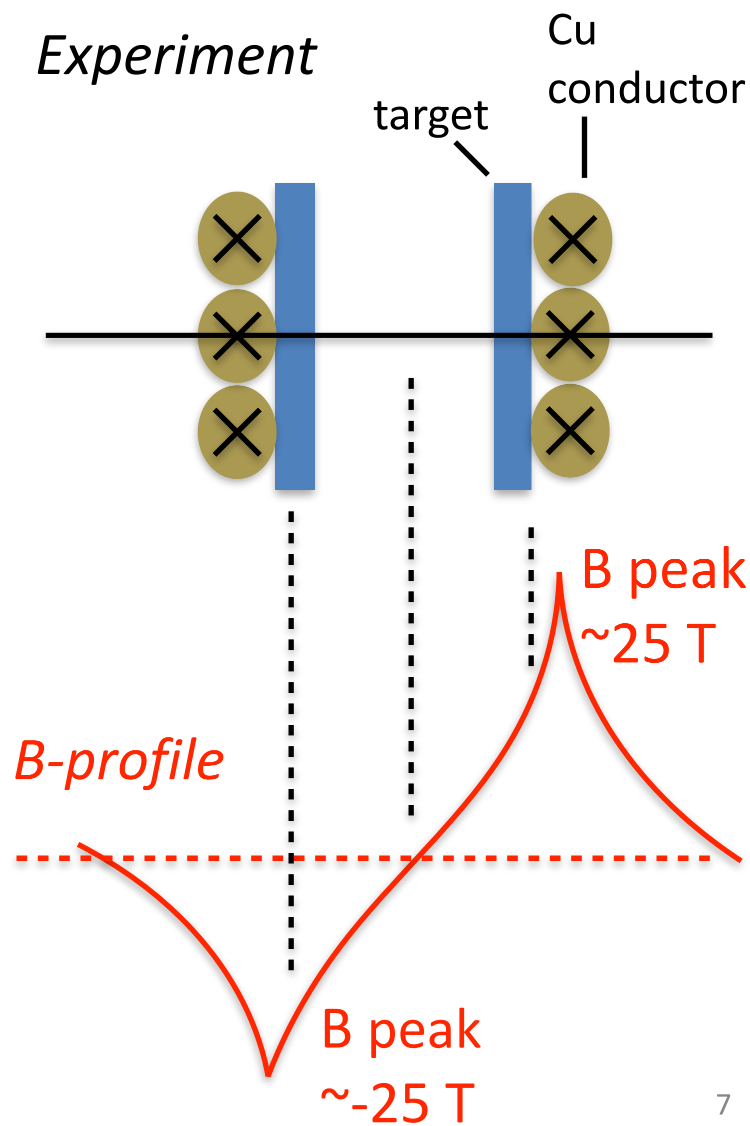
This experiment requires a B≥ 25 T and uniformity to 25%

This design has Bpeak ~ 25 T.

The geometry of the B field will be similar to EP. It varies roughly linearly between two targets with a null of B= 0 at the midplane.

Longitudinal uniformity as on EP; Probably 30% is sufficient.

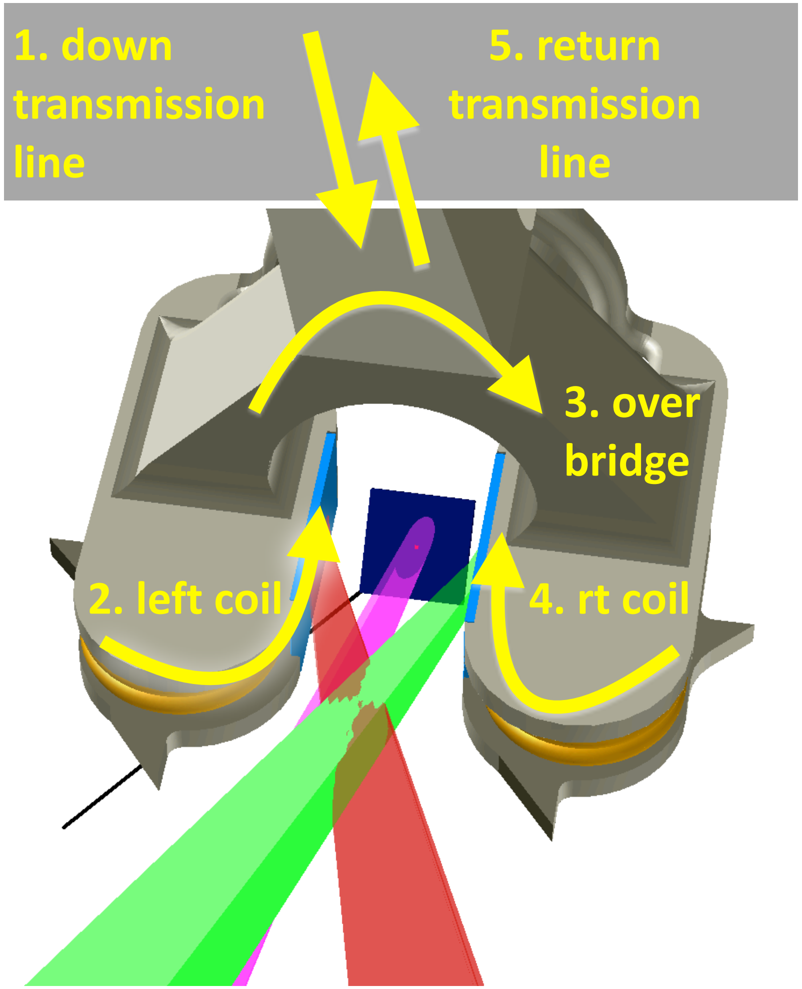
Our MIFEDS reconnection design uses 2 coils in series



This experiment requires a magnetized volume of ~50 cm^3

Critical experimental volume to magnetize for on NIF is ~3 cm^3. However significant "extra" volume is magnetized to close currents.

Total Magnetized volume on EP is a few cm^3. Scaling up by factor 3 in linear dimension for NIF, so perhaps ~50 cm^3 total



MIFEDS reconnection on EP

Rise time determined by target inertia & dissipation

There will be a rise time requirement associated with **mechanical stress** on the target.

A second rise-time requirement will be to **not melt coils** by ohmic dissipation in coils.

There are no metallic components apart from Cu coils conductors. Therefore no soak-through time

G. Fiksel designed around these issues for EP MIFEDS reconnection

Requirement: **Diagnostic access**

This experiment requires diagnostic access for these measurements…

The OMEGA EP experiments have an open geometry so diagnostic access has been typically easy.

Proton radiography. Want to send proton beam along current sheet. Detectors would go on an equatorial DIM, with Dh3 proton source on opposite side of experiment

Optical interferometry. On OMEGA EP, this required rotating MIFEDS coils off from the horizontal plane to align with probe beam.

Thomson scattering.

X-ray plasma temperature measurements

Bring up any other issues

OMEGA EP requires the MIFEDS reconnection experiments to run with a disposable debris shield over the short-pulse backlighter parabola due to large target mass

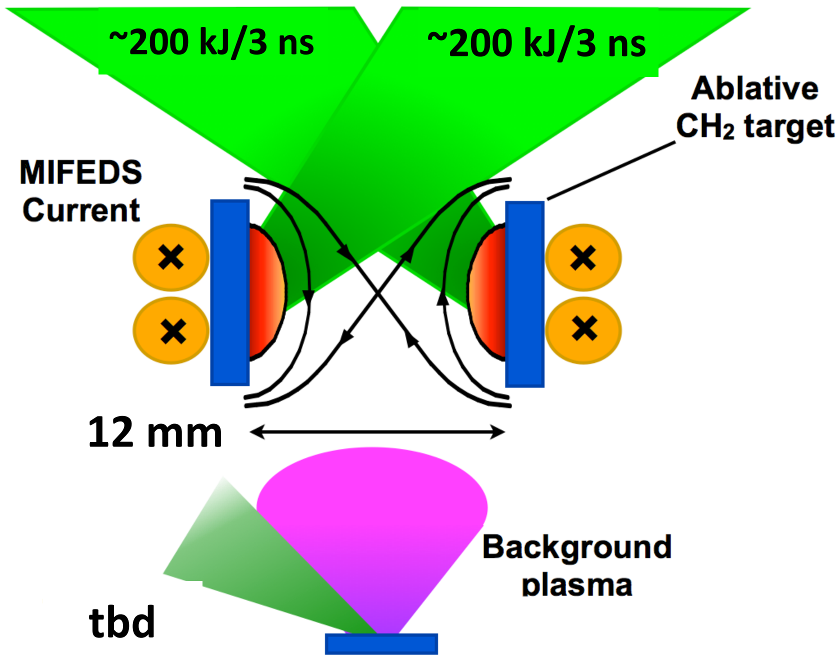
Summary

Experiment: Magnetic reconnection of externally-applied B fields

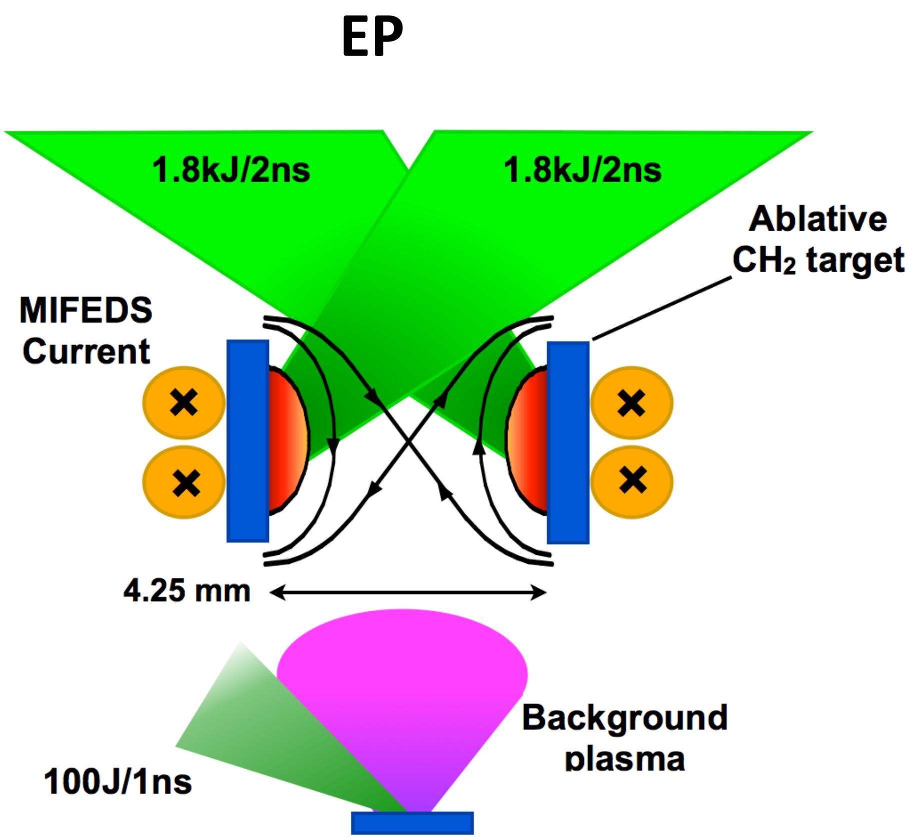
Summary requirements

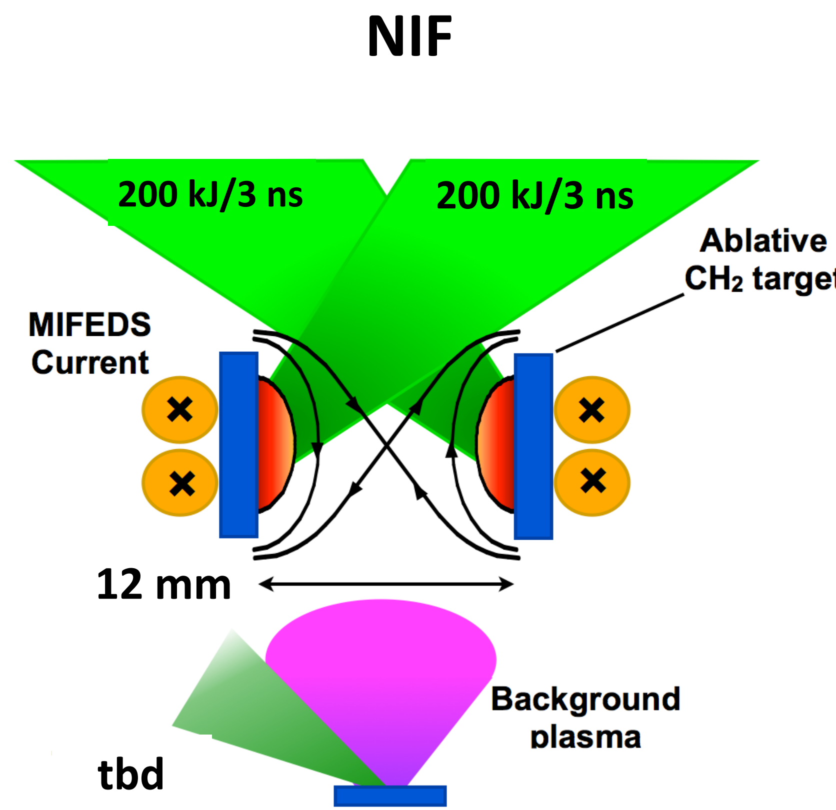
B-field magnitude	25 T peak values
B-field spatial shape / extent	reversing profile. Experimental volume ~ 3-4 cm
B-field uniformity	25% over the required volume
B-field rise time	tbd
Diagnostic access	Proton backlighter, x-ray, particle detector, optical interferometry and TS
Other	Significant target mass

Summary experiment sketch



(Easy, first) design based on geometric similarity scaling





2 page Physics summary (1)

Experiment: Pair confinement using a mirror magnetic field

Experiment: Pair confinement on NIF
Responsible Org: LLNL/Uni. Michigan
NIF shots from: TBD
Shot RI: Hui Chen and Gennady Fiksel
Engineer: TBD

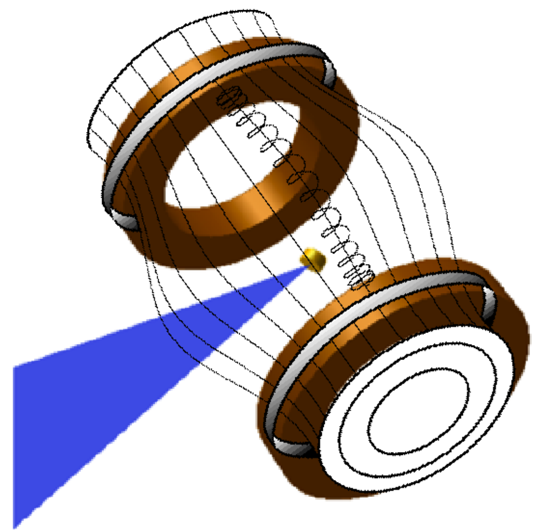
Experimental objectives: Establish a novel platform for basic science experiment on NIF.

Key physics related to having a B-field: First demonstration of pair confinement in the laboratory

Important aspects of the experiment:

- **Need mirror geometry >30 T B-fields**
- **Experiment date TBD**
- **The experiment can be done as a phased approach: the start point is pair collimation that needs <10 T field with single coil; then procced to double coils with ramping B-fields.**

Summary experiment sketch



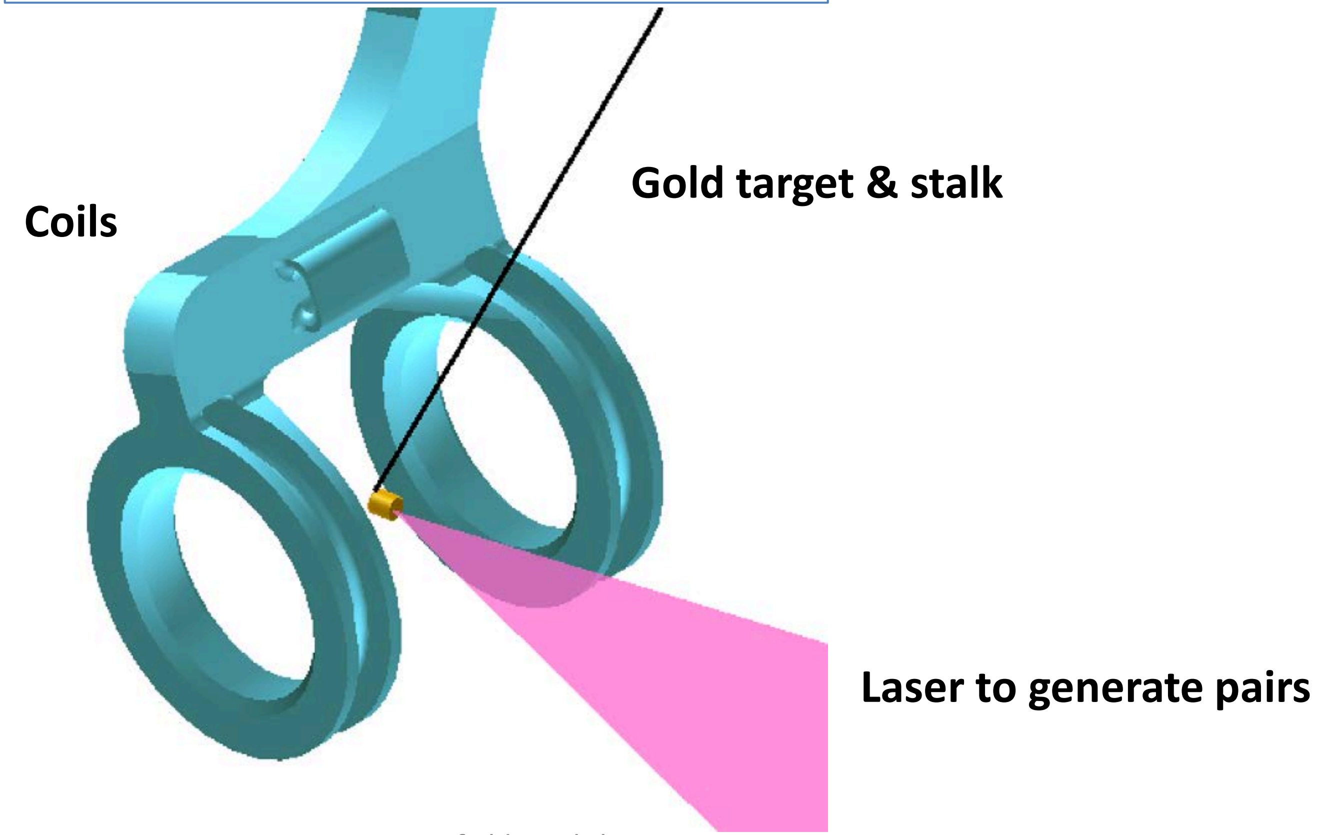
2 page Physics summary (2)

Experiment: Pair confinement using a mirror magnetic field

More detailed experimental sketch showing:

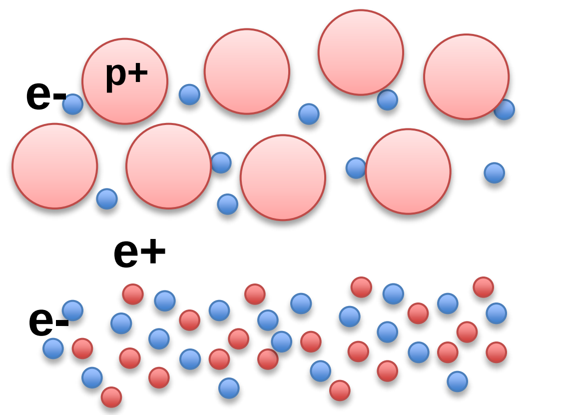
- NIF geometry; B-field direction; laser direction
- Key diagnostics – nEPPS

Possible experimental setup



The motivations of this project are derived from the need and feasibility of making a relativistic pair plasma using lasers

e-e+ plasmas are fundamentally different

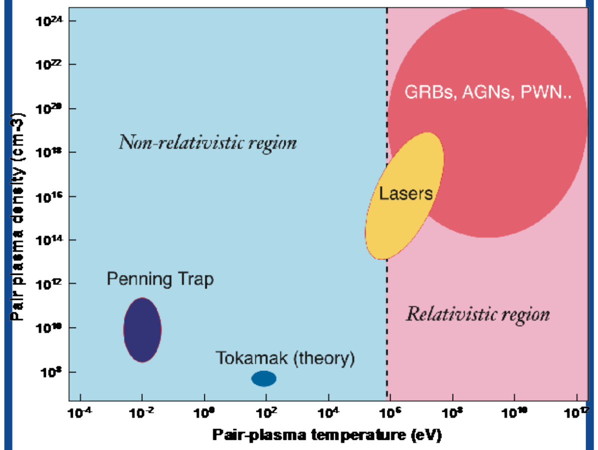


Tsytovich & Wharton (1978)
Linear polarization of cyclotron radiation
Nonlinear plasma processes (no 3-wave coupling, *M/m* larger nonlinear Landau damping)

Rel. e-e+ plasmas present only in astro. events

Wardle et al Nature (2008)
Mirabel & Rodriguez, Rev. Astro. Astrophy. (1999)
Surko & Greaves PoP (2004)
Betti Report (2009)

Pairs from lasers are unique in parameters

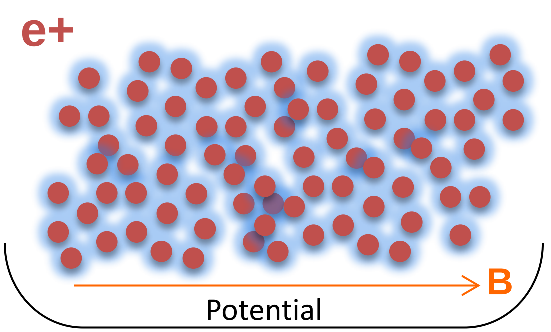


Chen et al HEDP (2012)
Chen et al. PoP (2014, 2015)

Establishing a novel matter-antimatter plasma using lasers in the laboratory will enable us to (1) study basic plasma physics and (2) probe the physics behind universe's most energetic events.

The capture of relativistic pair plasma has not been demonstrated at the laboratory

Single component e+ plasma was achieved

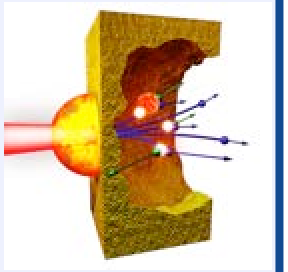


Using Penning trap by the Surko group at UCSD :

Surko, PRL 1989
Surko & Murphy Phys. Fluids 1990
Surko et al, Phys. Res. B 2000

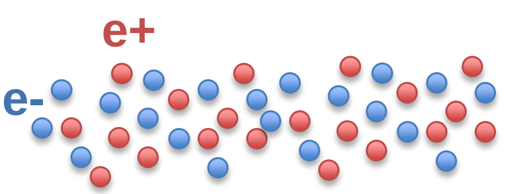
Laser pairs are good candidate for rel. plasma

Pair number: $10^{10} – 10^{12}$
Duration: ~10 - 100 ps
Pair rate: $\sim 10^{22}$ /s
Peak energy: 4 - 20 MeV
Peak flux: $>10^{25}\ cm^{-2}s^{-1}$
$T_{//}$: ~ 3 MeV;
$T_{\perp}$:~ 1 MeV
dE/E:50% - 20%
n_{e-}:$\sim 10^{13-15}\ cm^{-3}$
n_{e+}:$\sim 10^{12-14}\ cm^{-3}$



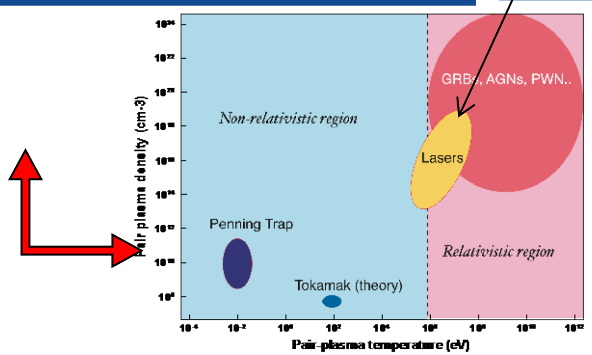
Chen et al. PRL 2009, 2010, HELP 2012, PoP (2014)

Three criteria of a true plasma



- ✓ **Sufficient number and size**
- • **Collective effect**
- ✓ **Charge neutral**

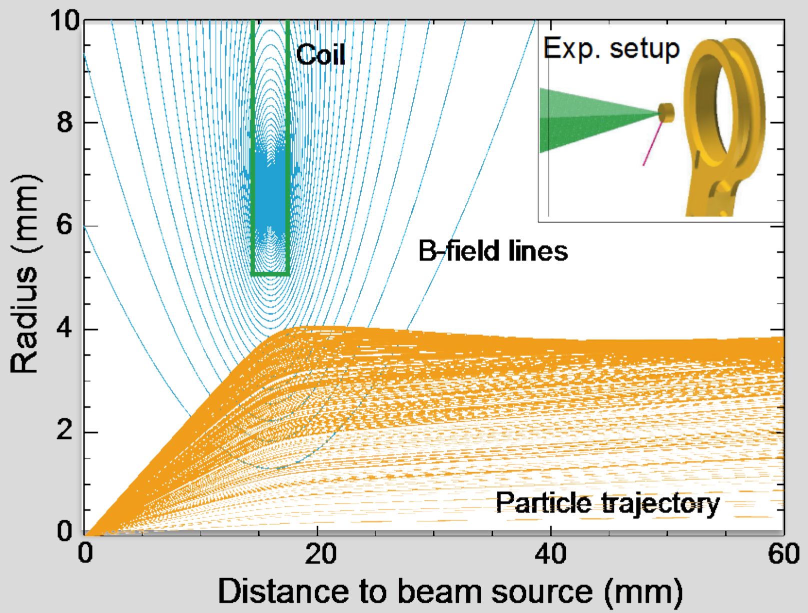
Wesson, 1997
Surko, Review in PoP, 2004



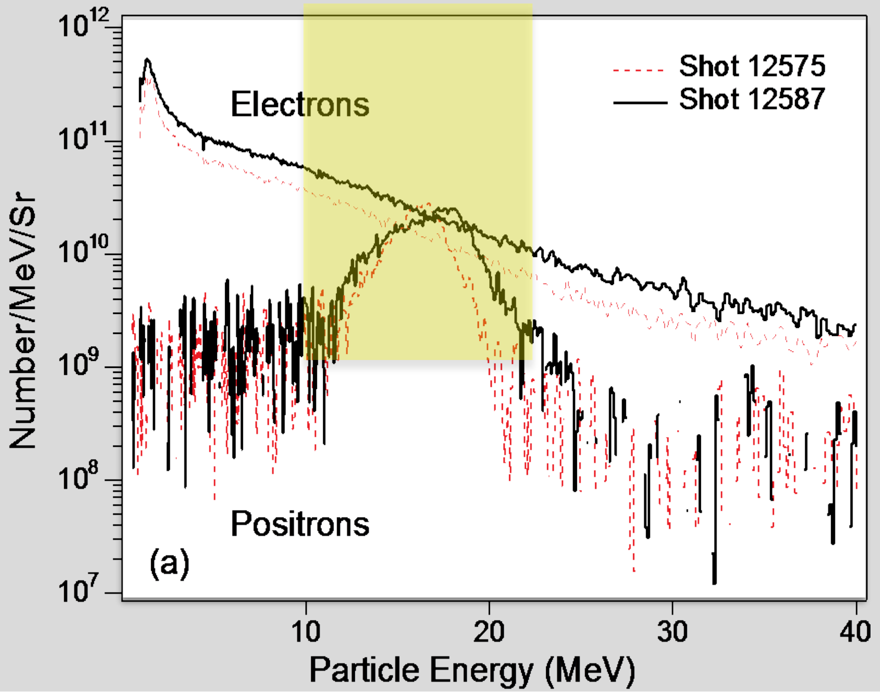
To capture the relativistic pairs and confine them for a duration of ~ns is challenging. It requires (1) suitable trapping device; (2) high strength (>10 T) magnetic fields; (2) controlled particle pitch angles; (3) accurate timing and (4) reliable diagnostics.

Recently, we have demonstrated effective collimation of laser-produced relativistic electron-positron pair jets

MIFEDS setup on OMEGA EP



e- & e+ spectra before collimation



More detail: Barnak Thurs. TO6-013

Chen, Fiksel, Barnak, et al., POP 2014

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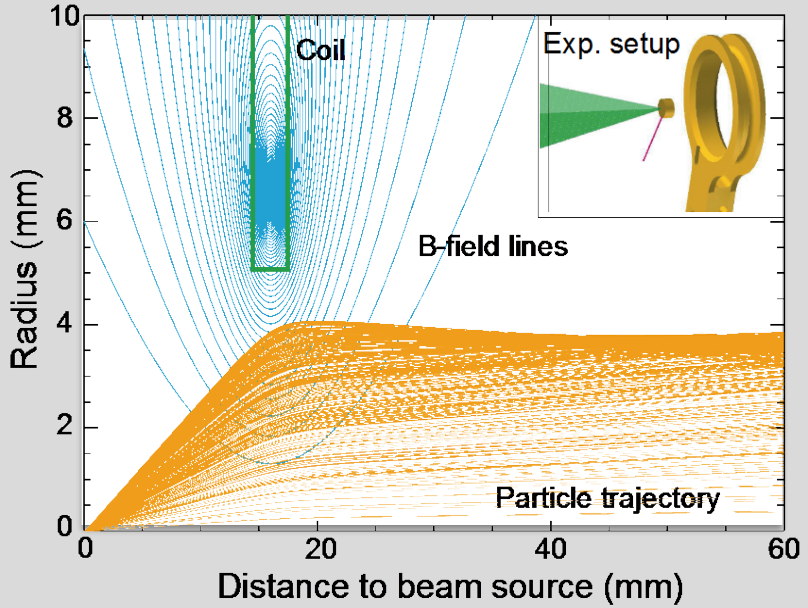
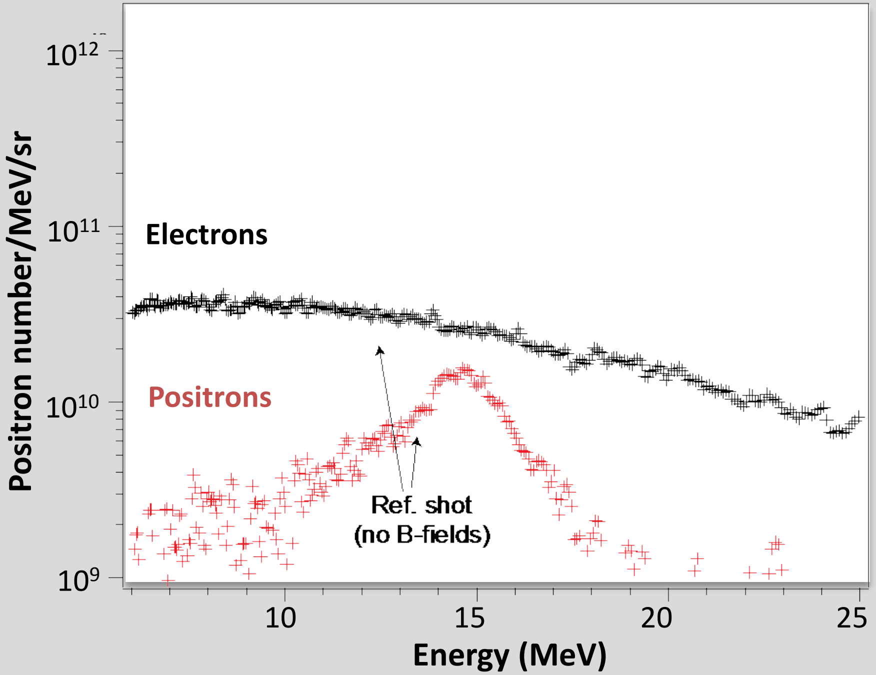


e- & e+ spectra before collimation



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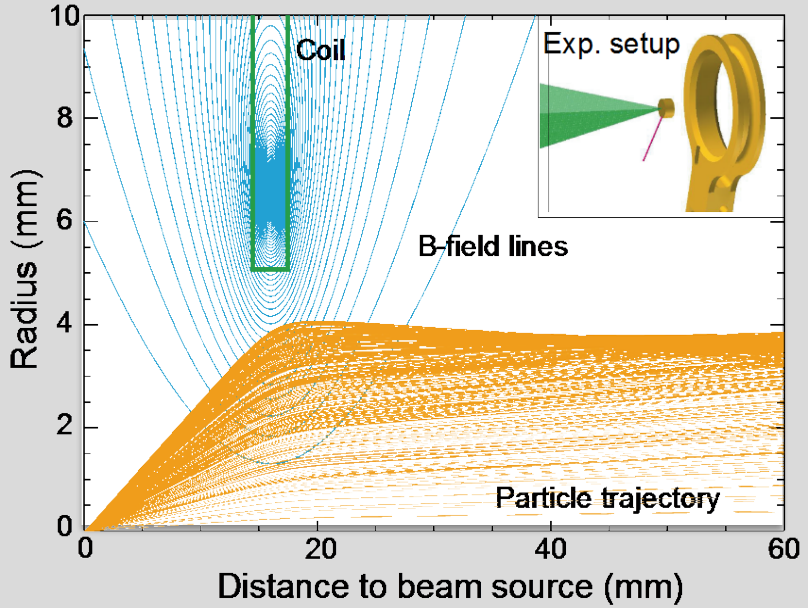
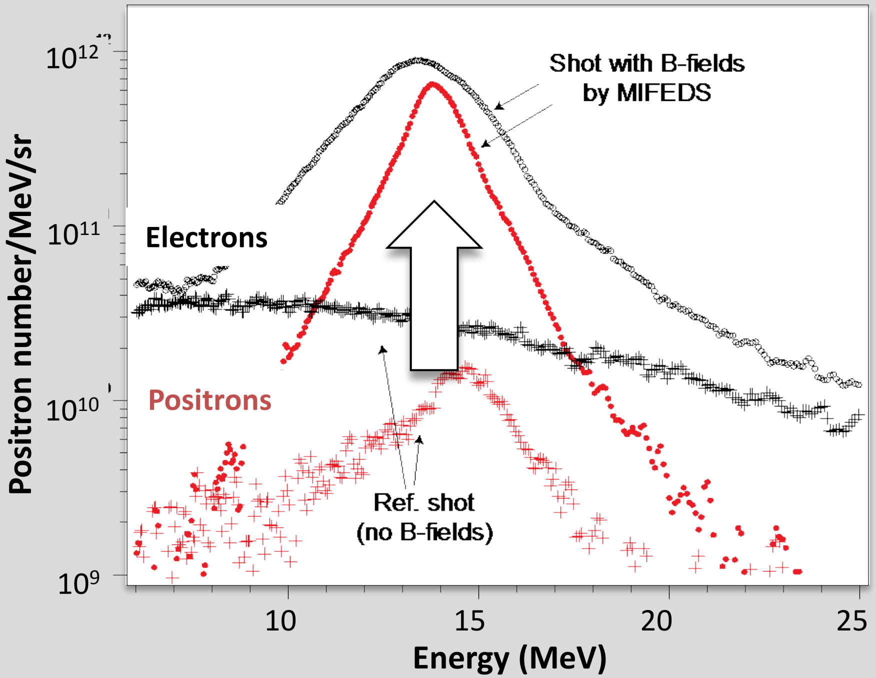


More detail: Barnak Thurs. TO6-013

e- & e+ spectra after collimation

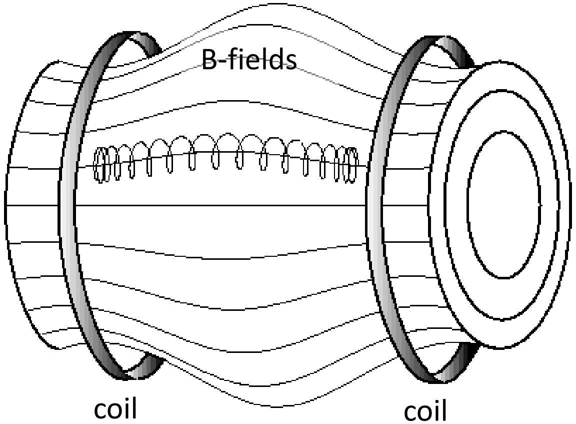


Chen, Fiksel, Barnak, et al., POP 2014

- The effective divergence of the beam reduced from 30 deg FWHM to 5 deg;
- The charge (e-/e+) ratio in the beam reduced from ~100 to 5.

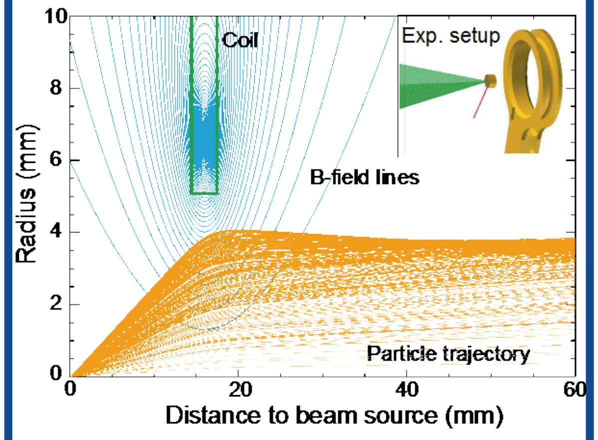
The objectives are to (1) establish techniques to make a suitable mirror B field; (2) demonstrate the capture of pairs

In theory mirror machine works for both charges



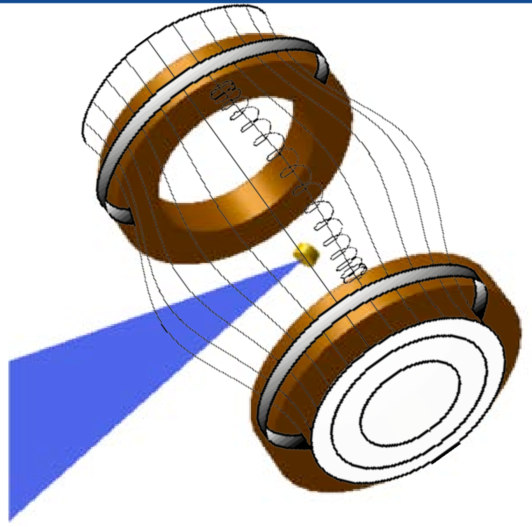
Gibson et al, PRL 1960
Pedersen et al, J. Phys. B 2003
Myatt, et al, PRE 2009

The first step: one coil has been demonstrated



Chen et al. PoP (2014)

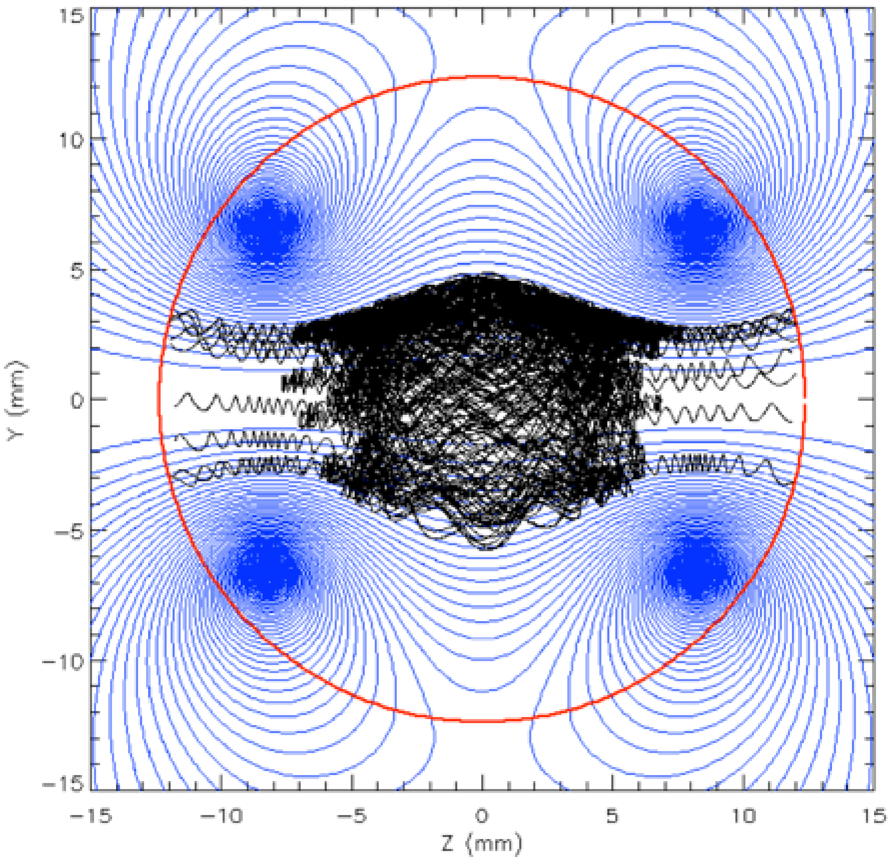
A double-coil system will form a mirror field



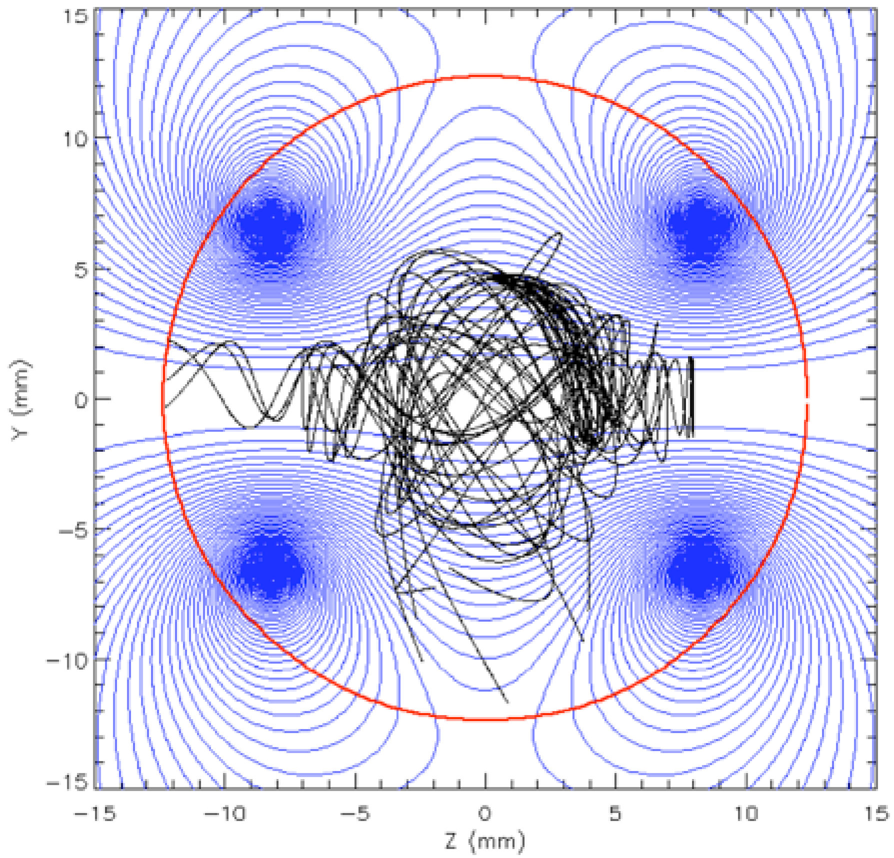
Theory and preliminary simulations show that using mirror fields, it is possible to trap MeV electrons and positrons produced from the laser-solid interaction – this will be studied and demonstrated in this project.

Simulations using LLE MIFEDS show that higher B-fields strength is needed to confine positrons at about 10 MeV

For 1 MeV electrons/positrons



For 5 MeV electrons/positrons

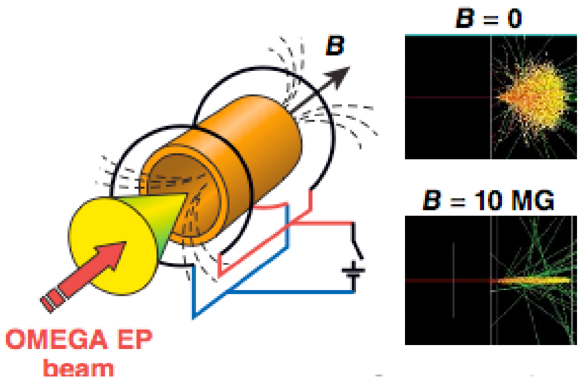


Simulations by G. Fiksel

Path forward for the confinement experiment on NIF

- Need a NIF MIFEDS that can deliver 30 – 40 T to allow up to 10 MeV pair jet confinement.
- Optimize the positron energy distribution for the trapping scheme
  - The optimal peak energy will be tuned using long-pulse lasers – a technique established by our group.
- Evaluate the alternative mirror B-fields from laser driven helmholz design
  - Maximum B-field strength vs control accuracy
- Demonstrate pair capturing using Laser experiments on Titan and Omega EP laser facility
  - Detection scheme using direct measurement
  - Fielding multilayer mirror for annihilation imaging purpose

Laser produced B-field setup



This experiment requires a B≥ 10 T and uniformity to 25%

One slide:

- B-field magnitude (range is fine)
- B-field spatial variation requirements (Solenoidal field, Helmholtz field, Cusp field, etc)
- B-field spatial uniformity requirements

This experiment requires a magnetized volume of 1 cm^3

One slide:

- Approximate magnetized volume
- Spatial shape of magnetized region
- Proposed source current path for achieving this

Requirement: B-field rise-time

This experiment requires the field to turn on no faster than 2 μs

One slide:

- Rise-time considerations (soak-in time, target distortions, etc)
- Rise time requirements

This experiment requires diagnostic access for these measurements…

One slide:

- Key measurements requiring diagnostic access
- Recommendations for achieving this

Bring up any other issues

One slide:

- Machine safety considerations (debris, laser damage, backscatter, diagnostic damage risk, etc)
- Feel free to share insights on working out solutions to any of these issues

Summary

Experiment: Few word descriptive name of the experiment

Summary requirements

B-field magnitude	**10 - 30 T**
B-field spatial shape / extent	**1 cm^3; cusp field shape**
B-field uniformity	**25% over the required volume**
B-field rise time	**2 μs**
Diagnostic access	**X-ray spectroscopy at several positions**
Other	**None**

Summary experiment sketch

Figure showing basics of the experiment